80 P.
NASA TM X-54,037

NSG-322-63
NSG-317-63
NASA TM X-54,037

N64-26593
Code-1 Cat. 05

THE IRON, MAGNESIUM, AND CALCIUM DISTRIBUTION IN COEXISTING OLIVINES AND RHOMBIC PYROXENES OF CHONDRITES

By Klaus Keil

Space Sciences Division
NASA, Ames Research Center
Moffett Field, Calif.

and

Kurt Fredriksson

University of California, ~~San~~
San Diego, Calif.

OTS PRICE
XEROX $ 2.60 ph.
MICROFILM $ _____

RC
#1

NASA TM X-54,037

The Iron, Magnesium, and Calcium Distribution in Coexisting Olivines and Rhombic Pyroxenes of Chondrites

KLAUS KEIL
Space Sciences Division, Ames Research Center
National Aeronautics and Space Administration
Moffett Field, California

KURT FREDRIKSSON
University of California, SIO, San Diego

26573 aw

ABSTRACT

Iron, magnesium, and calcium were analyzed in olivines and pyroxenes of 95 chondritic meteorites with an electron microprobe. Of these, 86 were 'ordinary' chondrites, each of which has constant iron-magnesium ratios in olivine and pyroxene. Between different meteorites these ratios vary within three narrow ranges, which reflect the H- and L-group chondrites [Urey and Craig, 1953], as well as a third group, designated the LL-group. The ratio of iron in olivine to that in coexisting pyroxene is nearly constant (~1.1), particularly within the groups mentioned. Based on the amount of iron in silicates and metal a classification of stony meteorites is proposed. It is shown that the iron content in the silicates is not related to the degree of metamorphism (recrystallization) and that, therefore, the composition of the silicates was essentially established when the chondrules were formed. Nor is the ferrous iron strictly related to the amount of metallic nickel-iron. Thus Prior's rule is not valid in its original sense, although it can be applied qualitatively when comparing the different groups of chondrites. It is demonstrated that coexisting olivines and pyroxenes are not in equilibrium in spite of their

constant composition and the constant ratio between their iron contents. Furthermore, the metallic nickel-iron seems to have originated in the same melt as did the silicates. author

INTRODUCTION

It has been previously observed that chondrites show varying degrees in their oxidation state. For example, enstatite chondrites are almost free of divalent and trivalent iron[1] and must have been formed under strongly reducing conditions. In carbonaceous chondrites, however, the iron is almost completely oxidized to the divalent and trivalent states, and only minor amounts of metallic nickel-iron occur in them. The ordinary chondrites show a state of oxidation somewhere between these extremes, containing varying but considerable amounts of metallic nickel-iron together with divalent iron compounds. Prior [1916a, 1920] attempted, in his classical papers, to correlate the mineralogical and chemical composition of the silicate minerals and the metallic nickel-iron in chondrites with the degree of oxidation. His conclusion, based mainly on bulk chemical analyses, was 'the less the amount of nickel-iron in chondritic stones, the richer it is in nickel and the richer in iron are the magnesium silicates.' This correlation, known since then as Prior's rule, has been accepted by most subsequent investigators and has been supported by later authors as Brown and Patterson [1947a,b; 1948] and, more recently, Ringwood [1961]. However, it has been questioned by Urey and Craig [1953] on the basis of their extensive study of 'superior' chemical analyses of

[1]Electron microprobe analyses of silicates from the enstatite chondrites St. Marks, Indarch, and Hvittis show small amounts of divalent iron.

chondrites available in the literature. Whether or not the iron content in the iron-magnesium silicates of chondrites can serve as a quantitative measure of the degree of oxidation is not yet certain. A comprehensive discussion of this problem, partly based on the data presented below, will be published by Suess (in press).

Another crucial problem for any hypothesis on the origin of chondrites is the existence of certain distinct groups among the chondritic meteorites. Urey and Craig demonstrated in 1953 the existence of two groups of chondrites, one having a low total iron content (22.33 weight per cent), the other a high content (28.58 weight per cent). These they designated the L-group and the H-group. The existence of these two groups can also be deduced from the metallic nickel-iron content and from the specific gravity [Keil, 1962a,b]. At present, it is not clear whether the two groups should be ascribed to two different parent bodies or two groups of bodies, as Urey and Craig suggested in 1953, or whether the L-group could have been derived from the H-group by loss of metallic nickel-iron, accompanied by recrystallization under slightly oxidizing conditions [Ringwood, 1961].

In the past years many hypotheses concerning the origin of chondrules and chondritic meteorites have been proposed (for a summary, see Mason [1962b]). Yet, it is quite generally agreed that chondrules originated as molten droplets which later accumulated into larger bodies. The structure of the chondrules and chondrites presumably has later been influenced by recrystallization and metamorphic processes (e.g., Sorby [1877]; Merrill [1921]; Kvasha [1958]).

Students of meteorites do not yet wholly agree whether the basic difference in oxidation state and in composition of the phases in chondrules and chondrites is due to varying conditions during the chondrule formation as is held by Ringwood [1961] or due to later recrystallization and metamorphism, accompanied by a diffusion of iron in solid state from magnetite assumed to be distributed throughout the matrix of the primitive chondrite into olivine and pyroxene inside the chondrules, producing the distributions now observed [Wood, 1962a,b; 1963a,b].

The present study was undertaken in the hope that more accurate data than formerly have been available on the composition of coexisting minerals in chondrites could give some clues to the problems outlined above. For this purpose the iron, magnesium, and calcium contents of coexisting olivine (isomorphous series of Mg_2SiO_4-Fe_2SiO_4) and rhombic pyroxene (isomorphous series of $MgSiO_3$-$FeSiO_3$) in a large number of different chondrites have been measured.

METHOD

In the past, the composition of coexisting olivines and rhombic pyroxenes in chondrites has been calculated from bulk chemical analyses (a process not always reliable Wiik [1956]), has been determined by analyzing mechanically separated pure mineral phases, has been measured optically, or it has been obtained by X-ray diffraction. The chemical analysis of separated phases is rather restricted because of the problems involved in clean separation of these phases from the complex intergrowths in chondrites. Furthermore, the chemical analysis

of separated phases gives the bulk composition of a large number of individual crystals of the same material without taking into account the possible variability in composition from grain to grain or the zonal structure. Nor can chemical analysis enable measurement of the composition of the occasionally occurring fine exsolution lamellae in pyroxenes, which differ in composition from the host pyroxene. Lastly, the error involved in the optical as well as the X-ray diffraction techniques is relatively high, amounting to some 10 per cent.

In comparison to use of those methods, the electron microprobe has proved to be a particularly useful tool for solving the problems mentioned. With the use of proper standards, the precision of the individual results is as good as ±0.1% Fe and ±0.2% Mg in olivine and rhombic pyroxene while the accuracy is in the order of ±0.3% Fe and Mg. Furthermore, the method is nondestructive and permits analysis of single grains, as small as a few microns in size, as well as of thin exsolution lamellae and crystals with zonal structure.

The measurements were made on polished sections of a diameter of 1.5 to 2.5 cm, which had been coated with a layer of carbon a few hundred Angstroms thick. The composition of olivines and rhombic pyroxenes in 95 chondrites was determined by using a modified ARL electron microprobe X-ray analyzer (ARL refers to Applied Research Laboratories, Glendale, California). This instrument is equipped with three dispersive monochromators which enable the measurement of three different elements (three different wavelengths) at the same time. Therefore, it was possible to measure Fe, Mg, and Ca simultaneously and in exactly the same position on the sample. At least

four analyses, 3 to 5 microns apart, were usually made on each grain. Some 20 to 30 olivine and rhombic pyroxene grains from each meteorite were measured. From each of the minerals with varying composition or zonal structure as many as several hundred grains were analyzed. The composition of the crystals was then ascertained by moving the sample in steps from 4 to 20 microns under the fixed electron beam, thus covering the grain with rows of analyses.

For the quantitative analysis of Fe and Mg in olivines, five chemically analyzed olivines and a pure forsterite (< 0.1 weight per cent Fe) from the Norton County achondrite [Keil and Fredriksson, 1963b] were used as standards, thus covering the range from pure Mg_2SiO_4 to 45.3 mol per cent Fe_2SiO_4. From the chemical analyses of these olivines (cf. Ross, et al., [1954] on olivines from Ludlow, California, and from Salt Lake Crater, Oahu, Hawaiian Islands; and also Yoder and Sahama [1957] on olivines from Susimaki, Finland, from Ultenthal, Tyrol, Austria, and from the Marjalahti, Finland, meteorite) the Fe and Mg values were calculated, the small amount of Fe_2O_3 being ascribed to magnetite inclusions. The chemical composition and the degree of homogeneity of these standards were controlled by using the microprobe to analyze them against pure metallic iron standards. After corrections were made for wavelength shift, detector deadtime, background, mass absorption, and atomic number,[2] agreement with the chemical analyses was found to be ±0.3% Fe. With use of the values given by the chemical analysis, Fe and Mg calibration curves were drawn for the olivines (fig. 1), and further values

[2]The fluorescence correction was found to be negligible.

were evaluated graphically. For Fe and Mg in rhombic pyroxenes, calibration curves were calculated theoretically from the olivine curves by applying the proper mass absorption corrections. In order to control the theoretical calibration curves for rhombic pyroxene, three pyroxenes with known composition were measured (two analyses by Engel, et al., in press, Nos. AC 362-Or and A 104-Or, and pure enstatite (< 0.1% Fe) from the Norton County achondrite). The theoretical curves for rhombic pyroxene are shown in figure 2. The Mg values of all three pyroxenes match the curve well within the precision of the technique. The zero point in the Fe curve is identical with the value of the enstatite from the Norton County achondrite. The Fe value of analysis AC 362-Or matches the theoretical curve closely. The Fe value of analysis A 104-Or differs somewhat. But this value according to the chemical analyses is considerably lower than the Fe values of the five other pyroxenes analyzed by Engel, et al. (in press), which have nearly the same composition with regard to the other elements present. Since, in particular, the Mg values of the two analyses are almost identical, it would seem that the chemically obtained Fe value of sample A 104-Or is somewhat too low, this being the probable reason for the disagreement with the theoretical curve and the analyses of the other rhombic pyroxenes.

The Ca content in rhombic pyroxene was measured by use of chemically analyzed andesine (Ca = 6.9; Al = 14.4; Si = 26.6 weight per cent) and the Ca-rich pyroxene samples A 104-Cl and AC 362-A (Engel, et al., in press) as standards, taking into account the mass absorption corrections. The precision was found to be ±0.1% Ca.

Although the accuracy of the results is chiefly dependent upon the quality of the calibration curves discussed above, the precision of the results depends on contamination effects caused by the electron beam on the spot to be analyzed, fluctuations in the electronics, and on the variability in composition of the standards. Since the analyses were always carried out with the same integration time, the contamination effect is negligible. Furthermore, it was found that optical refocusing did not affect the readout. In order to evaluate the effects of the electronic fluctuations and possible inhomogeneities in the standards, 20 measurements, in positions 3 microns apart, were made on the olivine standard Marjalahti. The precision was found to be ±0.1% Fe and ±0.2% Mg (Table 1).

RESULTS

The 95 different chondrites examined in the present study are included in alphabetical order in Table 2 showing the metal contents of some of the chondrites. They are numbered in the order of increasing iron in olivine. These numbers facilitate the finding of any one of the examined chondrites in Table 3, in which the analytical results are presented. These results have been recalculated and plotted in several other tables (4, 5, 6) and are shown in figures 4 to 12 in order to illustrate the facts discussed below. The results of studies of some other types of meteorites described elsewhere [Fredriksson and Keil, 1963; Keil and Fredriksson, 1963b; Mason, et al., in press] will be discussed so far as they are of significance to the present problems (cf. figs. 13 and 14).

The 95 meteorite samples were randomly selected from several meteorite collections without preference for one or the other type of chondrite. Finds were only included in the study as far as they were believed not to be altered by terrestrial oxidation and weathering. In the tables, the 18 finds are indicated by asterisks following their names. The results of the study are stated in the following four sections.

Constancy in Composition of Olivines and Rhombic Pyroxenes in Any Ordinary Chondrite

The analyses show that usually in a given meteorite the composition of olivines and rhombic pyroxenes is nearly constant. This fact has already been indicated by the sharp peaks found in X-ray diffraction patterns [Mason, 1960, 1963]. According to the microprobe results different olivine and rhombic pyroxene grains of a given chondrite vary less than ±1% Fe and Mg. Figure 3 shows an example. Analyses were made of 84 individual olivine grains from 17 different chondrules of different sizes from the Bjurböle chondrite. The results are plotted in a frequency distribution diagram, illustrating the remarkable uniformity in composition. (This uniformity was also observed for crystals in the matrix.) Table 7 lists the average composition of the 84 olivine grains as well as of 15 rhombic pyroxene grains (from 6 different chondrules) of the same meteorite.[3] Here again the rather small standard deviations for Fe, Mg, and Ca demonstrate the uniformity

[3]Much greater variations (olivine: 18 to 29% fayalite; rhombic pyroxene: 18 to 21% orthoferrosilite) reported by Wood [1962b] are probably due to inaccurate measurements.

in composition of those minerals. (For another example, compare the analyses of 155 individual olivines and 107 individual rhombic pyroxenes of the Pantar chondrite [Fredriksson and Keil, 1963].) Such constancy in composition of olivine and rhombic pyroxene holds true for 86 of the 95 chondrites studied (and listed in Table 3). The values given in this table are averages of several analyses of Fe and Mg in 10 to 20 olivines and of Fe, Mg, and Ca in 10 to 20 rhombic pyroxenes. The Ca content in olivine was found to be < 0.1 per cent. The $\frac{Fe}{Fe + Mg}$ ratios have been calculated from the Fe and Mg averages.

Since the precision of the microprobe measurements is high (±0.1% Fe, ±0.2% Mg), the average values given in Table 3 are characteristic numbers for any given chondrite which might, in connection with the different macroscopical and microscopical appearance of chondrites (color, degree of metamorphism, etc.), serve to identify mislabeled specimens.

Chondrites With Olivines and Pyroxenes of Varying Composition

In almost 10 per cent of the chondrites examined the olivines and pyroxenes vary in composition. Table 8 shows the results of analyses of individual olivines and pyroxenes from these meteorites. Unfortunately, from several of them only very small samples were made available for analysis. Consequently, sampling errors may affect the results; however, more detailed studies of these meteorites on larger samples are planned for the near future. The variability in composition of olivines and pyroxenes in the chondrites listed in Table 8 usually does not exceed 10 to 15 mol per cent $\frac{Fe}{Fe + Mg}$. Some of the crystals show zonal structure; others

do not. The grains listed in Table 8 which do not show zoning (i.e., which have only one value listed for Fe and one for Mg) may possibly have some zonal structure, which a chance orientation in the section plane might have prevented from being visible and having its variations measured. The chondrite Chainpur, in particular, is an example of a meteorite containing pyroxenes and especially olivines with distinct zonal structure. The difference in the $\frac{Fe}{Fe + Mg}$ ratios from the center to the rim is rather large in several crystals and sometimes it exceeds 10 mol per cent; some of the results are summarized in figure 13. In the Murray carbonaceous chondrite the individual olivine and pyroxene grains do not exhibit an extensive zoning, but their composition varies over a large range from grain to grain (olivine 0.3 to 91.2; pyroxene 0.4 to 45.4 mol per cent $\frac{Fe}{Fe + Mg}$, fig. 14). More detailed descriptions of the several hundred analyses of olivines and pyroxenes from the Chainpur chondrite and the Murray carbonaceous chondrite are given elsewhere [Mason, et al., in press; Fredriksson and Keil, in press].

The Relation Between Iron in Coexisting Olivine and in Rhombic Pyroxene of Chondrites

It has been pointed out above that for the majority of chondrites studied the composition of olivines as well as that of rhombic pyroxenes is nearly constant from grain to grain of a given meteorite. Only these meteorites have been plotted in the diagrams to be discussed.

In figure 4 the average mol per cent ratios $\frac{Fe}{Fe + Mg}$ in olivine have been plotted versus the $\frac{Fe}{Fe + Mg}$ ratios in the coexisting rhombic

pyroxenes. It is apparent that the points, each of which represents one chondrite, characteristically cluster into three distinct groups identical with the Urey-Craig [1953] L-group and H-group of chondrites and the Soko-Banja LL-group (Low iron-Low metal) established by Prior [1916a].

According to figure 4, the $\frac{Fe}{Fe + Mg}$ ratios of coexisting olivines and rhombic pyroxenes in chondrites are concentrated along an approximately straight line. (This fact is further illustrated in fig. 5.) Only the chondrite Ramsdorf deviates considerably. Although the sample available from it was very small, its pyroxene was found to have the highest calcium content noted among the chondrites studied, namely 1.1 per cent. (A more detailed study of the Ramsdorf meteorite, with larger samples, is planned for the near future.) The $\frac{Fe}{Fe + Mg}$ ratios in olivine are slightly higher than in coexisting rhombic pyroxene as figure 4 reveals and as had been previously noted by Mason [1962a]. In the diagram in figure 6 the differences

$$\left(\frac{Fe}{Fe + Mg}\right)_{olivine} \quad \text{minus} \quad \left(\frac{Fe}{Fe + Mg}\right)_{rh.\ pyroxene}$$

of the chondrites listed in Table 3 are plotted against the fayalite (Fe_2SiO_4) content of the olivines. This diagram shows that with increasing iron content in the silicates the difference between $\frac{Fe}{Fe + Mg}$ in olivine and $\frac{Fe}{Fe + Mg}$ in pyroxene also increases.

The LL-, L-, and H-Groups of Chondrites

The present analyses of olivine and rhombic pyroxene pairs indicate the existence of three distinct groups among chondrites

(see fig. 4). It is apparent that the first two groups are identical with the L-group and H-group chondrites of Urey and Craig [1953] and with the hypersthene and bronzite chondrites of Prior [1920]. The third group is identical with the Soko-Banja group chondrites of Prior [1916a]. Table 5 shows that the total iron content in the Soko-Banja group is almost the same as in the L-group chondrites, whereas the metallic nickel-iron content is considerably lower. For this reason the group constituted of Soko-Banja type chondrites should properly be designated the Low iron-Low metal (or LL-group) of chondrites.

Five among the 86 chondrites listed in Table 3 were found to belong to the LL-group. These are Cherokee Springs, Dhurmsala, Oberlin, Soko-Banja, and Vårvik. The $\frac{Fe}{Fe + Mg}$ ratios for olivine and rhombic pyroxene are distinctly higher in Vårvik than in the four other chondrites of this group. This possibly may suggest the existence of a fourth group, or of a subgroup; since adequate statistics are lacking this chondrite has simply been included in the LL-group.

The data presented indicate that the iron content in olivine and rhombic pyroxene can be an excellent criterión for classifying a specific chondrite in one of the three groups. Table 3 shows that the spread in the iron content of olivine and rhombic pyroxene within each group is rather small. In the LL-group it varies from 19.0 to 20.6 (olivine) and 11.2 to 12.3 (rhombic pyroxene); in the L-group it varies from 15.8 to 17.9 (olivine) and from 9.0 to 10.9 (rhombic pyroxene); and in the H-group it varies from 11.9 to 14.3 (olivine) and from 7.7 to 8.8 (rhombic pyroxene). As illustrated in figure 4,

all three groups are clearly defined. In figures 7 and 8, the $\frac{Fe}{Fe + Mg}$ ratios are plotted in frequency distribution diagrams for olivine and rhombic pyroxene. Again, the three groups, and likewise the sharp boundaries between them, are clearly recognizable.

The calcium content in the rhombic pyroxene, which varies within rather narrow limits, is not significantly different in chondrites of the LL-, L-, and H-groups, although there may be a slight tendency toward higher calcium content in those of the L-group in comparison with those of the H-group (figs. 9 and 10).

The average values for Fe, Mg, and $\frac{Fe}{Fe + Mg}$ in olivine, and for Fe, Mg, Ca, and $\frac{Fe}{Fe + Mg}$ in rhombic pyroxene, of the chondrites listed in Table 3, are given in Table 4, separated into LL-, L-, and H-groups, and a column for the total chondrites investigated. In Table 5 the various characteristic chemical-mineralogical parameters for LL-, L-, and H-group chondrites are compiled. On the basis of these parameters, the definite classification of a given chondrite into its proper group is possible.

DISCUSSION

The importance of the composition of coexisting olivines and pyroxenes for considerations related to the history of rocks has early been realized, and many important papers have been published dealing with chemical analyses and with theoretical calculations of these assemblages in plutonic, volcanic, and metamorphic rocks (e.g., Atlas [1952]; Bartholome [1962]; Bowen and Schairer [1935]; Brown [1957]; Brown, et al. [1961]; Hess [1941, 1949]; Hess and Phillips [1938, 1940];

Hori [1956]; Howie [1955]; Kuno [1954]; Kuno and Nagashima [1952]; Mueller [1960, 1961]; Muir [1951]; Muir and Tilley [1957, 1958]; O'Hara [1960]; Poldervaart [1947]; Poldervaart and Hess [1951]; Ramberg [1952]; Ramberg and DeVore [1951]; Ross, et al.[1954]; Sahama and Torgeson [1949a,b]; Schairer and Boyd [1956, 1957]; Wager and Deer [1939]; Wilson [1960]; Yoder and Sahama [1957]).

Systematic study of coexisting olivines and rhombic pyroxenes in meteorites has been made to much less extent. Most important are the studies of Hess and Henderson [1949], Mason [1962a], Mueller [1963], Prior [1916a], Ringwood [1961], and Wahl [1907].

Mason [1962a], who studied the composition of olivines by means of refractive index measurements in a large number of chondrites, published a frequency distribution diagram of the $\frac{Fe}{Fe + Mg}$ ratios in olivines, which agrees for the most part with figure 7 of the present study. His $\frac{Fe}{Fe + Mg}$ values seem to be systematically higher than those determined in the present study although the deviation is slight, amounting to only one mol per cent $\frac{Fe}{Fe + Mg}$. The LL-, L-, and H-group peaks are recognizable in his figures, but the boundaries between the groups are not so distinct as they are in figure 7 of the present study. This results from the fact that the error involved in the technique used by Mason is considerably higher being in the order of 10 per cent, which amounts to ±1.0 to ±1.5% Fe.

The Classification of Chondrites

Several classifications of meteorites and particularly of chondrites have been proposed in the past years [Brezina, 1904;

Prior, 1916a, 1920; Urey and Craig, 1953; Boato, 1954; Wiik, 1956; Mason, 1962a; Javnel, 1962, 1963], but a number of the supposedly 'newly discovered' groups were found to be identical with groups that earlier authors had already recognized and named. This led to the existence of a number of different terms for the same thing and has made the proper classification of chondrites complicated and often confusing, particularly for nonspecialists in this field. In addition to this situation, some further confusion is caused by improper use of some mineral names, particularly in the cases of the bronzite-olivine and hypersthene-olivine chondrites. It has been shown in the present paper that the ordinary chondrites do not contain rhombic pyroxene with hypersthene composition, but instead contain exclusively rhombic pyroxene with bronzite composition. The nomenclature of rhombic pyroxenes as initiated by Poldervaart [1947] and by Poldervaart and Hess [1951] is widely accepted in modern literature and handbooks on terrestrial rocks, and it should be adopted in regard to meteorite minerals as well. The classification suggested by Poldervaart [1947] is primarily chemical, and for the rhombic pyroxenes it is as follows: enstatite 0 to 10; bronzite 10 to 30; hypersthene 30 to 50; ferro-hypersthene 50 to 70; eulite 70 to 90; and orthoferrosilite 90 to 100 mol per cent $FeSiO_3$. In fact, the composition of the rhombic pyroxenes in bronzite-olivine and hypersthene-olivine chondrites varies within the ranges of 17.2 to 14.7 and 21.7 to 17.9 mol per cent, respectively; that is to say, per definition the rhombic pyroxene in both bronzite-olivine and hypersthene-olivine chondrites is bronzite. In order to avoid misunderstanding, it is therefore recommended that

the names High (H) and Low (L) iron groups of Urey and Craig [1953] be used instead. In the following paragraph a chondrite classification is proposed which is based on the best analytical data available. So as not to complicate the matter, an attempt has been made to use names which have some chemical-mineralogical significance and which are most commonly used by the majority of investigators in this field. For the LL-, L-, H-, and HL-groups of chondrites, the classification is based on two parameters, namely, the total iron and the metallic nickel-iron. The LL-, L-, and H-groups have been described in detail in the previous chapter and their characteristic chemical-mineralogical parameters have been summarized in Table 5. The group of chondrites consisting of meteorites of the Ornans type (the pigeonite chondrites of Mason [1962a]) have a total iron content similar to that in H-group chondrites, while their metallic nickel-iron content is considerably lower and varies in the order of 1 to 4 weight per cent [Wiik, 1956]. Therefore this group should properly be named High iron-Low metal (HL) group of chondrites. At the present time the enstatite chondrites cannot be classified in accordance with the principle outlined above since the available analyses show a highly varying amount of total iron. The total iron values range all the way from L-group to H-group chondrites, and even considerably above H-group chondrites. For this reason the customary name enstatite chondrites has been retained. The total iron content of the carbonaceous chondrites is similar to that of H-group chondrites, while their content of metallic nickel-iron is essentially zero. The classification principles mentioned have not been applied to this group because then the two subgroups of the

carbonaceous chondrites (type I and type II of Wiik [1956]) would be merged into one single group. Yet, basic mineralogical and chemical differences other than total iron content between the two subgroups are so striking that it seemed advisable to adopt the classification into type I and type II. The type III carbonaceous chondrites of Wiik [1956] are so characteristically different from the type I and type II that they seem to belong in still a separate group, the HL-group or pigeonite chondrites of Mason [1962a]. Type I carbonaceous chondrites do not contain chondrules and therefore (per definition) should not be designated chondrites at all. However, they have customarily been retained in that classification because they seem to be closely related to type II carbonaceous chondrites. It is hoped that further studies may allow a more precise mineralogical classification in the future.

In order to make the following compilation as complete as possible other names presently in use have been listed in parentheses.

A. Enstatite chondrites [Prior, 1920]

(Daniels Kuil type chondrites [Prior, 1916a]; group I chondrites [Javnel, 1962, 1963])

B. High iron (H)-group chondrites [Urey and Craig, 1953]

(Cronstad type chondrites [Prior, 1916a]; bronzite-olivine chondrites [Prior, 1920]; group II chondrites [Javnel, 1962, 1963])

C. Low iron (L)-group chondrites [Urey and Craig, 1953]

(Baroti type chondrites [Prior, 1916a]; hypersthene-olivine chondrites [Prior, 1920]; group III chondrites [Javnel, 1962, 1963])

D. Low iron-Low metal (LL)-group chondrites

(Soko-Banja type chondrites [Prior, 1916a][4]; these were included in the hypersthene-olivine chondrites by Prior [1920] and Mason [1962a]; group IV chondrites [Javnel, 1962, 1963])

E. High iron-Low metal (HL)-group chondrites

(Ornansites [Brezina, 1904]; included in the Soko-Banja group chondrites [Prior, 1916a], and in the hypersthene-olivine chondrites [Prior, 1920]; type II carbonaceous chondrites [Boato, 1954]; type III carbonaceous chondrites [Wiik, 1956]; pigeonite-olivine chondrites [Mason, 1962a]; group Va chondrites [Javnel, 1963])

F. Carbonaceous chondrites of type I and type II [Wiik, 1956]

a) Type I

(Included in the Soko-Banja group chondrites [Prior, 1916a], and in the hypersthene-olivine chondrites [Prior, 1920]; group Vc chondrites [Javnel, 1963])

---

[4]Prior [1916a] had in his Soko-Banja group nine chondrites which (on the basis of the new analytical data) actually belong to the L-group of chondrites. These nine are: Albareto, Alfianello, Bachmut, Bluff, Eli Elwah, Ergheo, Knyahinya, Mocs, and Nerft. He also originally included the carbonaceous chondrites and ornansites in this group although they consitute separate groups.

F. Carbonaceous chondrites of type I and type II [Wiik, 1956] - concluded.

b) Type II

(Included in the Soko-Banja group chondrites [Prior, 1916a], in the hypersthene-olivine chondrites [Prior, 1920], and in the type I carbonaceous chondrites of Boato [1954]; group Vb chondrites [Javnel, 1963])

It has been shown in previous chapters that the LL-, L-, and H-groups are defined by several mineralogical and chemical parameters (Table 5). It has been pointed out that on the basis of these parameters the classification of a given chondrite into one of these groups is possible. However, H. C. Urey has recently pointed out that in some unusual cases (e.g., McKinney) different classifications were possible for a given chondrite on the basis of these parameters. At the moment it is not clear whether this is due to (a) the existence of chondrites composed of fragments from different groups, (b) the existence of chondrites composed of a mixture of, for instance, a silicate matrix of one group with metallic nickel-iron of another group, or (c) errors in the analytical results which might be caused by either actual analytical errors and/or sampling errors due to use of terrestrially weathered chondrites or similar causes. At the present time, explanation (c) appears most reasonable. However, more detailed studies are necessary to decide this question.

Chemical Analyses of Chondrites and Prior's Rule

One result of the microprobe analyses of olivines and rhombic pyroxenes in chondrites during the present study is that the range in composition of these minerals in the different chondrites has been discovered to be surprisingly small, particularly if it be compared with the highly varying amounts of metallic nickel-iron in chondrites [Keil, 1962a,b]. Table 5 gives an indication of this striking situation. Figure 11 shows that the metallic nickel-iron content in the L-group chondrites, for instance, varies from 4.40 to 11.65 weight per cent, whereas the Fe content in olivines of the same group varies only from 17.9 to 16.3 and for rhombic pyroxene from 10.9 to 9.0 weight per cent. The amount of metallic nickel-iron has been plotted against the iron content in olivine and rhombic pyroxene of chondrites. Most of the metallic nickel-iron values were obtained by planimetric integration of large polished sections [Keil, 1962a,b]; the others are from 'superior' chemical analyses as given by Urey and Craig [1953], and from others published more recently by several other investigators (see Table 2). As has already been pointed out [Keil, 1962a,b] there is a systematic difference between the metallic nickel-iron contents obtained by chemical analyses and by planimetric integration. Wiik [1956] showed, on the basis of recent analyses, that the iron content of chondrites as given by Urey and Craig [1953] is probably somewhat too high. The results of the planimetric integration, on the other hand, could be somewhat too low since extremely small grains might have been overlooked under the microscope or might have been lost during the process of polishing the samples. However, this deviation

is likely to be less than 1 per cent nickel-iron. Yet the spread in the contents of metallic nickel-iron, as obtained by planimetric integration, seems to be real. Figure 11 shows that in spite of differing amounts of metallic nickel-iron the Fe content in olivine and rhombic pyroxene varies within narrow limits. The most important fact, however, is that within a given group there is no clear relationship between the amount of metallic nickel-iron and the Fe content in olivine and rhombic pyroxene of chondrites. The broken lines in figure 11 were calculated from the average composition of each group, assuming straight reduction-oxidation of iron and taking into account the resulting changes in mineralogical composition; that is, an increase of divalent iron increases the amount of olivine but decreases the amount of rhombic pyroxene, etc. The calculations are based on the averages given by Urey and Craig [1953] (Ni content); by Keil [1962a,b] (metallic nickel-iron and troilite contents); and by Mason [1962b] (feldspar and olivine-rhombic pyroxene ratios). The average composition of olivine and rhombic pyroxene was taken from the numbers given in the present study. The disagreement of the slope of these lines with the actually measured values indicates that the second part of Prior's rule in its original sense ('the less the amount of nickel-iron in chondritic stones . . . the richer in iron are the magnesium silicates') is not valid.

However, if the chemically obtained metallic nickel-iron values (circles in fig. 11) were disregarded then some relation between metallic nickel-iron and divalent iron within single groups (particularly H-group) could possibly be inferred, but any such relation is by no means general and does not follow the theoretical red-ox lines in

figure 11. Since the metallic nickel-iron values might still be affected by an error of some 5 per cent an attempt was made to correlate the chemically obtained nickel values with the amount of divalent iron in olivine and rhombic pyroxene, but no characteristic relation with the few 'superior' nickel analyses available in the literature has been observed. Accurate nickel determinations (~1 per cent of the values) on sufficiently large samples seem to be needed to settle this question.

On the basis of the average composition of L- and H-group chondrites as given above, a simple calculation has been made in order to evaluate a reduction-oxidation process accompanied by removal of metallic nickel-iron.

Starting with the average H-group composition, it was found that about 4.5 per cent metallic iron has to be oxidized in order to change the composition of the proper amounts of olivine and rhombic pyroxene to the values of the L-group chondrites. While some iron is being oxidized into the divalent state, the nickel remains reduced in the metallic nickel-iron, thus increasing its nickel content in an amount corresponding to the 4.5 per cent metallic iron being oxidized. A certain amount of the metallic nickel-iron has to be removed in order to give the amount now observed in the average of the L-group. After the removal of the proper amount, the amount of nickel left in the chondrite can be calculated. The calculated value (~1.18% Ni) agrees well (within 8 per cent) with the average nickel content (1.06 per cent) in the L-group [Urey and Craig, 1953]. This calculation does not necessarily imply that the L-group condrites were formed by oxidation of pre-existing H-group chondrites, but it indeed seems

to support Ringwood's [1961] suggestion that 'the Low-iron group is essentially a member of the parental High-iron group from which a small proportion of iron has been removed.' A further discussion of such a model and some of its difficulties will be given in the next chapter.

On this basis, it seems that although some reduction-oxidation of iron might have occurred, Prior's rule cannot be applied quantitatively because removal of metallic nickel-iron is necessary to account for a relation of oxidized versus metallic iron as observed in figure 11.

It has already been mentioned that after Prior's [1916a, 1920] pioneering work most subsequent workers have supported the second part of his rule. Their studies were mainly based on a comparison of metallic nickel-iron with FeO values obtained by bulk chemical analyses. Those data seem to support strongly the second part of that rule. However, the data of the present study make the use of chemically obtained FeO values doubtful. In fact, it seems as if the relation expressed in the second part of Prior's rule in its original sense is a direct result of erroneous FeO determinations by means of chemical analyses. The wet chemical determination of FeO in chondrites, which contain iron in metal, sulfides, and silicates, is known to be extremely difficult. It may be designated the most uncertain value in a chondrite analysis [Wiik, 1956] since it is derived by subtraction after three separate analyses. Usually in such an analysis the metallic nickel-iron is determined independently by magnetic separation or by using various solvents. Iron in the sulfide

is calculated from the amount of sulfur present. A third determination gives the total iron. The FeO is then computed as follows:

$$Fe_{oxidized} = Fe_{total} - \left(Fe_{FeS} + Fe_{metal}\right)$$

Generally, the FeS tends to be too high since all the sulfur is calculated as FeS without taking into account the presence of some minor minerals such as CaS, $FeCr_2S_4$, and others. Much more serious are some other uncertainties which might, in particular, affect the value of the iron in the metal. Most important in this connection is the problem of sampling errors. The metallic nickel-iron is inhomogeneously distributed throughout a given meteorite [Keil, 1962a,b]. The use of too small samples for the analysis could influence the results considerably. In addition, some of the metallic nickel-iron is included in silicates and will only partly be dissolved in the analytical procedure. Although correction can be made by measuring the Ni content of the silicate portion, a considerable error may be introduced owing to inhomogeneous Ni distribution. Furthermore, broken surfaces of chondrites show that even in case of fresh falls the nickel-iron oxidizes and becomes surrounded by a brownish oxide rim. As a result, the values for the metal will be too low, and this, in turn, brings up the values for the oxidized iron according to the formula. In fact, any error in the value of the metallic iron will affect the oxidized iron values in the opposite direction, thus creating artificially a relation such as is expressed in the second part of Prior's rule. Chemical errors as the cause for this accidentally created rule, which was based on bulk chemical analyses, was

already proposed by Urey and Craig [1953], a point of view which appears to be favored by the data of the present study. This is illustrated in figure 12 on the basis of the numbers compiled in Table 6. In figure 12 the $\frac{Fe}{Fe + Mg}$ values according to chemical analysis are plotted against the $\frac{Fe}{Fe + Mg}$ ratios of olivine-rhombic pyroxene pairs of different chondrites according to the microprobe analyses. On the assumption that olivine and rhombic pyroxene are the only major minerals containing FeO, and that both microprobe and chemical analyses are correct, the lines connecting coexisting olivines with rhombic pyroxenes for a given chondrite should intersect a 45^{o} line. This is the case for only some of the chemical analyses, while in most cases the $\frac{Fe}{Fe + Mg}$ values given by the chemical analyses are considerably higher in comparison with the microprobe results. Besides, the spread in the chemically obtained $\frac{Fe}{Fe + Mg}$ values is much higher than for the microprobe data. Only a few analyses seem to be 'superior' with regard to the FeO, such as several by Wiik, Borgstrom, and Prior. Nevertheless, even a few of the more recent analyses, such as by Wiik, Clark, and others, deviate markedly, although in the case of the two finds analyzed by Wiik this is very likely due to terrestrial oxidation of metal to oxide.

It is not likely that some minerals with high FeO in the extremely fine-grained matrix could cause these deviations since the more reliable chemical analyses agree better with the data of the present study. Furthermore, a special search for minerals containing large amounts of divalent iron in the fine-grained matrix of the Kyushu chondrite, for which a marked discrepancy between chemical

analysis and the present data is apparent (Table 6), was negative. No such minerals have been found by stepping with the probe across the fine-grained matrix; nor have any silicates with iron contents higher than that of olivine been observed in any of the other ordinary chondrites investigated.

On the Origin of Chondrules and Chondritic Meteorites

Many models have been proposed for the origin of chondrules and chondritic meteorites. Most investigators, however, seem to agree that chondrules must have formed through rapid crystallization of liquid droplets, as is indicated by the presence of devitrified glass in chondrules, the frequent occurrence of skeleton crystals, the drop-like shape of the chondrules, the presence of high-temperature plagioclase, and the occasional indentation of one chondrule by another. These droplets would later have accumulated to form chondrites. From the present results it seems clear that the composition of olivine and pyroxene with regard to iron content was essentially established when the crystals were formed. This is contrary to a hypothesis recently published by Wood [1962a,b; 1963a,b]. He suggested that molten silicate droplets could originate through condensation in a gas cloud of solar composition; in this case the silicates would have low iron content (< 2% Fe). Wood therefore suggested that the ferrous iron now present in olivine and pyroxene was introduced by diffusion in solid state from magnetite (Fe_3O_4), assumed to be present in the matrix of the primitive chondrite, into the silicates of the chondrules during a subsequent metamorphic process. Although most chondrites

have doubtlessly been recrystallized and metamorphosed, this apparently did not cause any major changes in the composition of the Mg-Fe silicates, but mainly resulted in changes of the structure, porosity, and compactness of the meteorites, as discussed in detail below.

Chondrites of different groups (LL-, L-, and H-groups) are characterized by typical $\frac{Fe}{Fe + Mg}$ ratios of their olivines and rhombic pyroxene as is illustrated in figure 4. According to Wood's model, chondrites with higher $\frac{Fe}{Fe + Mg}$ ratios in these minerals should be highly recrystallized, while the ones with low ratios should be less recrystallized. In order to compare the degree of metamorphism[5] with the iron content of the silicates, thin sections of 35 analyzed chondrites were examined microscopically. In both L- and H-groups there are chondrites showing a wide range of metamorphism, from friable stones with pronounced chondritic structure to well-indurated ones with chondrules inseparable from, or even completely integrated with, the groundmass. However, no connection between degree of metamorphism, as determined in this way, and composition of the olivines and rhombic pyroxenes was found. One example is the meteorite Tieschitz, a typical unmetamorphosed chondrite [Wood, 1962a, 1963b] which, however, contains olivines and pyroxenes with high, varying amounts of iron [Wood, 1962b]. (Microprobe analyses show up to 11.9% Fe in olivine, and up to 8.9% Fe in pyroxene.)

---

[5]As defined by most earlier workers, including Wood, through the indistinctness of the chondrules from the matrix, the relative uniformity of grain size, appearance of the plagioclase, etc.

Another finding, which contradicts Wood's proposition that the iron content in the silicates of chondrites is secondary, concerns some rather unmetamorphosed chondrites like Murray (Fredriksson and Keil, in press) and Chainpur (detailed microprobe results in Mason, et al. [1963]). These very friable meteorites contain a high percentage of olivine and pyroxene sometimes with extremely high content of ferrous iron (cf. figs. 13 and 14). Since these chondrites are in a rather unmetamorphosed stage they should, according to Wood's hypothesis, not contain any appreciable amounts of iron in the silicates. A characteristic feature of these chondrites is that they contain olivines and pyroxenes of highly varying composition (Murray: olivine 0.3 to 91.2, pyroxene 0.4 to 45.4, fig. 14; Chainpur: olivine 0.1 to 36.1, pyroxene 0.9 to 25.9, $\frac{Fe}{Fe + Mg}$ mol per cent, fig. 13). As emphasized by Fredriksson [1963] it is unlikely that in an in situ recrystallization, as proposed by Wood, some olivine and pyroxene grains would remain as almost pure Mg silicates, while others, only a fraction of a millimeter away, would increase in iron to high concentrations particularly in the presence of carbon. Of particular interest in this connection is the Chainpur chondrite. Several hundred olivine and pyroxene crystals were analyzed from 50 chondrules of different sizes. In figure 13 some of the results are summarized. Since the crystals are zoned, the averages of the values measured in a given crystal have been plotted. The diagrams illustrate the variability in composition from crystal to crystal as discussed above. In addition, they indicate that smaller chondrules tend to contain less iron in olivines and pyroxenes than do the larger ones, a fact

which again contradicts the possibility of a secondary origin of the iron content in these silicates. If the $\frac{Fe}{Fe + Mg}$ ratios were due to diffusion in solid state of iron, the silicates in the small chondrules should be richer, or at least equally as rich, in iron as the silicates in the large ones.

The olivines and pyroxenes in the Chainpur chondrite show marked zonal structure; that is, the core of the crystals is Mg rich, while the iron content progressively increases towards the outer rims of the crystals. This is in accordance with what would be expected when olivine and pyroxene crystallize from a melt at a rapid rate, however somewhat slower than in the quenched chondrules of ordinary chondrites.

These findings indicate that the composition of the chondrules was essentially established before they agglomerated.

As already explained above, chondrules appear to have originated by rapid cooling (quenching) of molten droplets, which then accumulated to form chondrites. In such a process it seems highly unlikely that olivine-rhombic pyroxene pairs would crystallize in equilibrium, although the almost constant ratios of $\frac{(Fe)_{olivine}}{(Fe)_{rh.\ pyroxene}}$ may seem to indicate this (fig. 4). This constancy, however, could be explained in another way [Fredriksson, 1963]. If the droplets were quenched, olivine would precipitate first, in a matter of seconds, and would have an almost constant composition. The residue may solidify as glass which may devitrify into plagioclase and orthopyroxene (usually formed below 1075°C) during subsequent slower cooling, possibly after accumulation of the chondrules, or later reheating. The feasibility

of such a process has been shown by Fredriksson and Ringwood [1963]. The varying composition of olivines and pyroxenes in Chainpur type chondrites and in the ones listed in Table 8 may simply be due to somewhat slower cooling than in ordinary chondrules so that zonal structure could develop. This is substantiated by the unusually high Ca content in the Chainpur pyroxenes which indicates that this mineral had time to crystallize at higher temperatures, possibly directly from the melt.

Furthermore, if coexisting olivines and pyroxenes are compared with Bowen and Schairer's [1935] data on the MgO-FeO-SiO_2 system, it appears that they are not at equilibrium at any temperature. The olivine is too rich in Mg (or the pyroxene in Fe); this seems consistent with a rapid crystallization, producing Mg-rich olivine and an Fe enriched glass, later recrystallizing mainly to pyroxene and plagioclase. The deviation from equilibrium is particularly pronounced above 1400°C, which is of interest because chondritic silicate would be almost entirely crystallized below this temperature. From the droplike shape of the chondrules it is concluded that about 70 per cent or more of the material was still liquid when the droplets were formed. This would require temperatures around 1500°C to 1550°C. For the present qualitative discussion it therefore seems justified to use the 1550°C isothermal plane of Bowen and Schairer's [1935] MgO-FeO-SiO_2 phase equilibrium diagram. This is shown in figure 15 with points plotted as follows: L_{sil} and H_{sil} show the MgO, FeO, and SiO_2 (recalculated to 100 per cent) for the average L- and H-group chondrites; L_{tot} and H_{tot} were obtained by calculating the total iron (including Fe in

metal and troilite) as FeO, thus assuming that all iron was once oxidized; similarly, O_{tot} indicates the composition of the Orgueil carbonaceous chondrite. These values are based on the data given by Urey and Craig [1953]. Finally, L_{ol} and H_{ol} show the composition of the average olivine compositions for L- and H-group chondrites as given in Table 4. It is immediately apparent that melts of L_{sil} or H_{sil} composition could hardly precipitate olivine of the observed composition. However, partial reduction of a melt of composition H_{tot} (or O_{tot}) may yield L- and H-group chondrites with the proper olivines and proper amounts of metallic nickel-iron. If, for example, metallic nickel-iron would segregate by reduction from a silicate melt of composition H_{tot} but not be removed from the system, a point on the H_{tot}-H_{sil} line would be reached where H-group olivine could precipitate leaving the bulk composition within the H-group range. If from the same melt (H_{tot}) some of the segregated metallic nickel-iron is removed, a composition could be reached where L-group olivine could precipitate and the total melt reach the L_{tot} point. Apparently more ferrous iron than now observed was present during the formation of the meteoritic olivines, part of which is now observed as metallic nickel-iron. It is also clear that some further reduction must have occurred during or after the chondrule formation as also was suggested by Ringwood [1961]. Presence of a metallic iron phase during the silicate formation is further indicated by the low Ni content of the chondritic olivines (see p. 34). It has been suggested that metallic nickel-iron in chondrites could have been introduced mechanically [Urey and Mayeda, 1959]. They thought that the occurrence of kamacite,

taenite, plessite, and the morphology of the metal particles could best be accounted for by assuming the grains to be fragments of slowly cooled 'primary bodies' which have been mixed with the silicate portion subsequent to the chondrule formation to give the 'secondary bodies.' The main argument for this proposal seems to be that the metallic particles in chondrites apparently cooled slowly. However, this can be accounted for, even if chondrules, metal, and interstitial matter solidified rapidly, by assuming that the chondrites remained at more moderate temperatures (e.g., 500°C to 700°C, [Urey and Mayeda, 1959]) after agglomeration for a longer period of time, for example, simultaneously with the recrystallization of the glass to pyroxene and plagioclase. However, besides the results discussed above, several other observations indicate that the metallic nickel-iron was formed from the same melt as the silicates. Several of these observations are listed below, some of which have already been discussed by Ringwood [1961] and Urey [1963].

(a) Fredriksson [1963] showed that some chondrules of the Bjurböle chondrite contain as much nickel-iron as the matrix. Microscopic estimates indicate that this is the case also in other chondrites. The apparently larger size of the metal particles in the matrix may be due to later recrystallization [Fredriksson, 1963]. The metallic particles inside the chondrules obviously constitute a coexisting phase and can hardly be explained by a mechanical mixing of solid particles after chondrule formation.

(b) The amount of metallic nickel-iron stays within characteristic ranges in LL-, L-, and H-group chondrites (LL-group 1.72 to 3.23; L-group 4.40 to 11.65; H-group 14.17 to 19.81, in weight per cent [Keil, 1962a,b]). This fact indicates a close genetical relationship between metal and silicate (as do the previously discussed phase relations).

(c) The amount of Ni in chondritic olivine[6] is considerably lower than in most terrestrial olivines. Meteoritic olivine should contain higher amounts than observed unless the nickel was scavenged by metallic iron during the formation of the chondritic silicates as is in the case for many chondrules (see (a), p. 33). Consequently, it seems likely that the olivine in the matrix of the chondrites is also formed in the presence of molten metal.

(d) The irregular shape of the nickel-iron grains in chondrules is apparently due to the fact that the metal solidified last (together with troilite), when only small interstitial spaces were left between the largely solidified silicates, rather than due to fragmentation of solid nickel-iron and mixing with silicates. The occasionally observed fragmentation and distortion of nickel-iron grains ('veins' cutting iron grains into fragments, e.g., fig. 8(e) in Urey and Mayeda [1959]) can be explained by mechanical shock deformation in situ [Fredriksson et al., 1963].

---

[6]Recent microprobe analyses by Frederiksson (unpublished) show maximum Ni contents of 120-200 ppm Ni in olivine from Bjurböle (L-group) and approximately 100 ppm in Assisi (H-group). The pyroxenes in both chondrites seem to contain less nickel. The Marjalahti olivine (used as iron standard, p. 6) contained between 50-150 ppm Ni, which agrees with the analyses quoted by Mason [1962b] for pallasites.

The present investigation indicates that ordinary chondrites are nonequilibrium, cogenetic assemblages of silicates, mainly olivine and pyroxene, and metal. These results, together with other existing evidence, permit the assumption that L- and H-group chondrites could have originated from the same parent material (in one of several parent bodies). Consequently, this study supports a model for the origin of chondrites as proposed by Fredriksson [1963], a modification of the ideas presented by Ringwood [1961].

ACKNOWLEDGEMENTS

We wish to express our appreciation to Professors Gustaf Arrhenius, Hans E. Suess, and Harold C. Urey for stimulating discussions and many ideas. Professor Suess pointed out the importance of the iron content of the silicates in regard to the oxidation state of the chondrites and persuaded us to extend the work to its present volume. His continuous personal interest and encouragement is much appreciated. Professors T. G. Sahama, C. Ross, A. E. J. Engel, and C. G. Engel kindly provided us with their analyzed standard olivines and pyroxenes. The specimens for this study were made available to us through the generous cooperation of Drs. E. P. Henderson, B. Mason, C. Moore, H. E. Suess, H. Wänke, and F. E. Wickman. We are indebted to Professor F. E. Wickman, who first suggested this investigation, and for support from the Swedish National Science Research Council (Contract 2245-2, 1959-1960) for the first microprobe work at the Metallographic Institute in Stockholm. Thanks are due to Miss B. Koontz for correcting the manuscript and for many of the calculations and sample preparations, the latter together with Miss D. Bryan. The main part of the research was carried out under NASA Grant NsG-322 and NsG-317-63 from the National Aeronautics and Space Administration, and NSF-G-12325 from the National Science Foundation. One of us (Klaus Keil) has been supported in part by a National Academy of Sciences - National Research Council Resident Research Associateship. The generous support from these agencies is gratefully acknowledged. All experimental work was carried out in the La Jolla Microprobe Laboratory. The results were first presented at the Gordon Conference on Physics and Chemistry of Space at Tilton, New Hampshire, June 2-6, 1962.

REFERENCES

Atlas, L., The polymorphism of $MgSiO_3$ and solid-state equilibria in the system $MgSiO_3$-$CaMgSi_2O_6$, J. Geol., 60, 125-147, 1952.

Bartholome, P., Iron-magnesium ratio in associated pyroxenes and olivines, Petrologic Studies; A volume to honor A. F. Buddington, Geol. Soc. Amer., 1-20, 1962.

Boato, G., The isotopic composition of hydrogen and carbon in the carbonaceous chondrites, Geochim. et Cosmochim. Acta, 6, 209-220, 1954.

Borgström, L. H., Der Meteorit von St. Michel, Bull. Comm. Geol. Finlande, 34, 1-49, 1912.

Bowen, N. L., and J. F. Schairer, The system MgO-FeO-SiO_2, Amer. J. Sci., 29, 151-217, 1935.

Brezina, A., The arrangement of collections of meteorites, Proc. Amer. Phil. Soc., 43, 211-247, 1904.

Brown, H., and C. Patterson, The composition of meteoritic matter, I. The composition of the silicate phase of stony meteorites, II. The composition of iron meteorites and the metal phase of stony meteorites, III. Phase equilibria, genetic relationship, and planet structure, J. Geol., 55, 405-411, 1947a; 55, 508-510, 1947b; 56, 85-111, 1948.

Brown, G. M., Pyroxenes from the early and middle stages of fractionation of the Skaergaard intrusion, East Greenland, Min. Mag., 31, 511-543, 1957.

Brown, W. L., N. Morimoto, and J. V. Smith, A structural explanation of the polymorphism and transitions of $MgSiO_3$, J. Geol., 69, 609-616, 1961.

Clarke, R. S., Chemical composition of the Harleton, Texas meteorite, preprint, 1962.

Craig, H., Petrological and compositional variations in meteorites, Isotopic and Cosmic Chem.; A volume dedicated to H. C. Urey, North-Holland Publishing Company, Amsterdam, in press.

Daubree, G. A., Meteorite tombee le 19, Mars 1884, a Djati-Pengilon (ile de Java), Compt. rend. Paris, 105, 203-205, 1887.

Duke, M., D. Maynes, and H. Brown, The petrography and chemical composition of the Bruderheim meteorite, J. Geophys. Res., 66, 3557-3563, 1961.

Eberhardt, P., and J. Geiss, Meteorite classes and radiation ages, Isotopic and Cosmic Chem.; A volume dedicated to H. C. Urey, North-Holland Publishing Company, 1963.

Engel, A. E. J., C. G. Engel, and R. G. Havens, Mineralogy of amphibolite interlayers in the Gneiss complex, Northeast Adirondack Mountains, New York, J. Geol., in press.

Fredriksson, K., Chondrules and the meteorite parent bodies, Trans. New York Acad. Sci., Ser. II, 25, 756-769, 1963.

Fredriksson, K., P. S. De Carli, and A. Aaramäe, Shock-induced veins in chondrites, Space Res. III, North-Holland Publishing Company, Amsterdam, 1963.

Fredriksson, K., and K. Keil, The light-dark structure in the Pantar and Kapoeta stone meteorites, Geochim. et Cosmochim. Acta, 27, 717-739, 1963.

Fredriksson, K., and K. Keil, The Fe, Mg, Ca, and Ni distribution in coexisting minerals in the Murray carbonaceous chondrite, Meteoritics, in press.

Fredriksson, K., and A. E. Ringwood, Origin of meteoritic chondrules, Geochim. et Cosmochim. Acta, 27, 639-641, 1963.

Gallitelli, P., Sulla meteorite caduta in Albareto di Modena nel luglio 1766, Period. Min. Roma, 10, 345-378, 1939.

Hadding, A., Der Ekeby Meteorit, Forh. Geol. Foren., Stockholm, 62, 148-160, 1940.

Hess, H. H., Pyroxenes of common mafic magmas, Amer. Min., 26, 515-535; 573-594, 1941.

Hess, H. H., Chemical composition and optical properties of common clinopyroxenes, Amer. Min., 34, 621-666, 1949.

Hess, H. H., and E. P. Henderson, The Moore County meteorite: A further study with comment on its primordial environment, Amer. Min., 34, 494-507, 1949.

Hess, H. H., and A. H. Phillips, Orthopyroxenes of the Bushveld type, Amer. Min., 23, 450-456, 1938.

Hess, H. H., and A. H. Phillips, Optical properties and chemical composition of magnesian orthopyroxenes, Amer. Min., 25, 271-285, 1940.

Hori, F., Effects of constituent cations on the refractive indices of orthopyroxenes, Min. J. Japan, 1, 359-371, 1956.

Howard, K. S., and J. M. Davison, The Estacado aerolite, Amer. J. Sci., 21, 186; 22, 55-60, 1906.

Howell, E. E., W. F. Hillebrand, and G. P. Merrill, Beaver Creek meteorite, Amer. J. Sci., 47, 430-435, 1894.

Howie, R. A., The geochemistry of the charnockite series of Madras, India, Trans. Roy. Soc. Edin., LXII, 725-768, 1955.

Javnel, A. A., Correlations of various forms of iron in chondrites, Meteoritika, 22, 74-82, 1962, (in Russian).

Javnel, A. A., On genetic relationships in chemical composition of chondrites, Meteoritika, 23, 36-41, 1963, (in Russian).

Keil, K., On the phase composition of meteorites, J. Geophys. Res., 67, 4055-4061, 1962a.

Keil, K., Quantitative-erzmikroskopische Integrationsanalyse der Chondrite., Chem. d. Erde, 22, 281-348, 1962b.

Keil, K., and K. Fredriksson, Electron microprobe analysis of some minerals in stony meteorites (abstract), Soc. Appl. Spectroscopy, 2nd Natl. Meet., 31-32, 1963a.

Keil, K., and K. Fredriksson, Electron microprobe analysis of some rare minerals in the Norton County achondrite, Geochim. et Cosmochim. Acta, 27, 939-947, 1963b.

Kuno, H., Study of orthopyroxenes from volcanic rocks, Amer. Min., 39, 30-46, 1954.

Kuno, H., and K. Nagashima, Chemical composition of hypersthene and pigeonite in equilibrium in magma, Amer. Min., 37, 1000-1006, 1952.

Kunz, G. F., Forest City meteorite, Trans. New York Acad. Sci., 9, 200, 1890.

Kvasha, L. G., On the thermal metamorphism in some stone meteorite types, Meteoritika, 16, 156-174, 1958.

Lindstrom, G., Analys af de vid Stalldalen den 28, Juni, 1876, nedfallna meteorstenar, Overs. Svenska Vetensk, Akad. Forh., 34, 35-40, 1877.

Mallet, J. W., A stony meteorite from Coon Butte, Arizona, Amer. J. Sci., 21, 347-355, 1906.

Mason, B., The origin of meteorites, J. Geophys. Res., 65, 2965-2970, 1960.

Mason, B., The classification of chondritic meteorites, Amer. Mus. Novitates, 2085, 1-20, 1962a.

Mason, B., Meteorites, John Wiley and Sons, Inc., New York, 1962b.

Mason, B., Olivine composition in chondrites, Geochim. et Cosmochim. Acta, 27, no. 10, 1011-1024, 1963.

Mason, B., and H. B. Wiik, The Tomhannock Creek, New York chondrite, Min. Mag., 32, 528-534, 1960.

Mason, B., and H. B. Wiik, The Kyushu, Japan chondrite, Geochim. et Cosmochim. Acta, 21, 272-275, 1961a.

Mason, B., and H. B. Wiik, The composition of the Ottawa, Chateau-Renard, Mocs, and New Concord meteorites, Amer. Mus. Novitates, 2069, 1-25, 1961b.

Mason, B., and H. B. Wiik, The Holbrook, Arizona chondrite, Geochim. et Cosmochim. Acta, 21, 276-283, 1961c.

Mason, B., H. B. Wiik, K. Keil, and K. Fredriksson, The Chainpur meteorite, Amer. Mus. Novitates, 1963, in press.

Merrill, G. P., On metamorphism in meteorites, Bull. Geol. Soc. Amer., 32, 395-414, 1921.

Merrill, G. P., A stony meteorite from Forksville, Mecklenburg County, Virginia, Proc. U. S. Natl. Mus., 70, no. 2670, art. 21, 1-4, 1927.

Merrill, G. P., and H. N. Stokes, A new stony meteorite from Allegan, Michigan, and a new iron meteorite from Mart, Texas, Proc. Wash. Acad. Sci., 2, 41-56, 1900.

Mueller, R. F., Compositional characteristics and equilibrium relations in mineral assemblages of a metamorphosed iron formation, Amer. J. Sci., 258, 449-497, 1960.

Mueller, R. F., Analysis of relations among Mg, Fe, and Mn in certain metamorphic minerals, Geochim. et Cosmochim. Acta, 25, 267-296, 1961.

Mueller, R. F., A comparison of oxidative equilibria in meteorites and terrestrial rocks, Geochim. et Cosmochim. Acta, 27, 273-278, 1963.

Muir, I. D., The clinopyroxenes of the Skaergaard intrusion, Eastern Greenland, Min. Mag., 29, 690-714, 1951.

Muir, I. D., and C. E. Tilley, Contributions to the petrology of Hawaiian basalts, I. The picrite basalts of Kilauea, Amer. J. Sci., 255, 241-253, 1957.

Muir, I. D., and C. E. Tilley, The composition of coexisting pyroxenes in metamorphic assemblages, Geol. Mag., 95, 403-408, 1958.

Nordenskiold, A. E., Der Meteorsteinfall bei Hessle in Schweden am 1. Januar 1879, Ann. Physik, 141, 205-244, 1870.

O'Hara, M. J., Co-existing pyroxenes in metamorphic rocks, Geol. Mag., XCVII, 498-503, 1960.

Pisani, F., Analyse de la météorite de Kernouve, prés Cleguerec, arrondissement de Napoleonville (Morbihan), tombee le 22, Mai 1869, Compt. rend. Paris, 68, 1489-1491, 1869.

Pokrzywnicki, J., The specific gravity of meteorites, Acta Geophys. Polonica, 6, 127-152, 1959.

Poldervaart, A., The relationship of orthopyroxene to pigeonite, Min. Mag., 28, 164-172, 1947.

Poldervaart, A., and H. H. Hess, Pyroxenes in the crystallization of basaltic magma, J. Geol., 59, 472-489, 1951.

Prior, G. T., On the genetic relationship and classification of meteorites, Min. Mag., 18, 26-44, 1916a.

Prior, G. T., The meteorite stones of Launton, Warbreccan, Cronstad, Daniels Kuil, Khairpur, and Soko-Banja, Min. Mag., 18, 1-25, 1916b.

Prior, G. T., The chemical composition of the meteorites Amana (Homestead) and Eagle Station, Min. Mag., 18, 173-179, 1918.

Prior, G. T., The classification of meteorites, Min. Mag., 19, 51-63, 1920.

Prior, G. T., and M. H. Hey, Catalogue of Meteorites, British Museum Press, London, 1-432, 1953.

Ramberg, H., Chemical bonds and distribution of cations in silicates, J. Geol., 60, 331-355, 1952.

Ramberg, H., and G. De Vore, The distribution of Fe^{++} and Mg^{++} in coexisting olivines and pyroxenes, J. Geol., 59, 193-210, 1951.

Rammelsberg, C. F., Uber den Meteorstein von Chantonnay, Z. Deutschen Geol. Ges., 22, 889-892, 1870.

Ramsay, W., and L. H. Borgström, Der Meteorit von Bjurböle bei Borga, Bull. Comm. Geol. Finlande, no. 12, 28 pp, 1902.

Rath, G. v., Mineralogische Mitteilungen uber den Meteoriten von Girgenti, Ann. Physik, 138, 541-545, 1869.

Ringwood, A. E., Chemical and genetic relationships among meteorites, Geochim. et Cosmochim. Acta, 24, 159-197, 1961.

Ross, C. S., M. D. Foster, and A. T. Myers, Origin of dunites and of olivine-rich inclusions in basaltic rocks, Amer. Min., 39, 693-737, 1954.

Sahama, Th. G., and D. R. Torgeson, Some examples of the application of thermochemistry to petrology, J. Geol., 57, 255-262, 1949a.

Sahama, Th. G., and D. R. Torgeson, Thermochemical study of the olivines and orthopyroxenes, Bur. Mines Rept. Investigations, 4408, 1-24, 1949b.

Schairer, J. F., and F. R. Boyd, Pyroxenes, Ann. Rept. Dir. Geophys. Labor., Washington, 223-225, 1956, 1957.

Sorby, H. C., On the structure and origin of meteorites, Nature, 15, 495-498, 1877.

Suess, H. E., The Urey-Craig groups of chondrites and their state of oxidation, Isotopic and Cosmic Chem.; A volume dedicated to H. C. Urey, North-Holland Publishing Company, Amsterdam, in press.

Tipper, G. H., The Merua meteorite, Rec. Geol. Survey India, 56, 345-351, 1925.

Urey, H. C., A review of atomic abundances in chondrites and the origin of meteorites, preprint, 1963.

Urey, H. C., and H. Craig, The composition of the stone meteorites and the origin of the meteorites, Geochim. et Cosmochim. Acta, 4, 36-82, 1953.

Urey, H. C., and T. Mayeda, The metallic particles of some chondrites, Geochim. et Cosmochim. Acta, 17, 113-124, 1959.

Vilcsek, E., Der Meteorit von Breitscheid, II. Chemische Analyse, Geochim. et Cosmochim. Acta, 17, 320-322, 1959.

Wager, L. R., and W. A. Deer, Geological investigations in East Greenland, Part III. The petrology of the Skaergaard intrusion, Kangerdlussuaq. Medd., 105, no. 4, 1-353, 1939.

Wahl, W. A., Die Enstatitaugite, Tschermak's Min. Petrogr. Mitt., 26, 1-131, 1907.

Wahl, W. A., A check on some previously reported analyses of stony meteorites with exceptional high content of salic constituents, Geochim. et Cosmochim. Acta, 1, 28-32, 1950a.

Wahl, W., The statement of chemical analyses of stony meteorites and the interpretation of the analyses in terms of minerals, Min. Mag., 29, 416-426, 1950b.

Wiik, H. B., The chemical composition of some stony meteorites, Geochim. et Cosmochim. Acta, 9, 279-289, 1956.

Wilson, A. F., Coexisting pyroxenes: some causes of variation and anomalies in the optically derived compositional tie-lines, with particular reference to charnockitic rocks, Geol. Mag., XCVII, 1-17, 1960.

Wood, J. A., Chondrules and the origin of the terrestrial planets, Nature, 194, 127-130, 1962a.

Wood, J. A., Metamorphism in chondrites, Geochim. et Cosmochim. Acta, 26, 739-749, 1962b.

Wood, J. A., On the origin of chondrules and chondrites, Icarus, 2, no. 2, 152-180, 1963a.

Wood, J. A., Chondrites and chondrules, Sci. Amer., 209, no. 4, 65-82, 1963b.

Yoder, H. S., and Th. G. Sahama, Olivine X-ray determinative curve, Amer. Min., 42, 475-491, 1957.

Table 1.- Homogeneity of the Mineral Standards and Precision of the Individual Fe and Mg Microprobe Analyses. Example: Olivine Standard Marjalahti (Fe = 8.5; Mg = 29.2 Weight Per Cent). Twenty Measurements, Each Position 3 Microns Apart. Standard Deviation: $S_{Fe} = \pm 0.07 \sim \pm\underline{0.1}$; $S_{Mg} = \pm 0.17 \sim \pm\underline{0.2}$

	Fe		Mg	
Position number	Measured intensity minus background	Content, weight %	Measured intensity minus background	Content, weight %
1	27.9	8.47	80.4	29.11
2	27.8	8.44	80.5	29.15
3	27.7	8.41	80.0	29.00
4	27.5	8.35	79.8	28.90
5	27.8	8.44	80.0	29.00
6	27.9	8.47	80.9	29.29
7	28.1	8.53	80.4	29.11
8	27.9	8.47	80.0	29.00
9	28.2	8.56	80.9	29.29
10	28.4	8.62	81.3	29.44
11	28.2	8.56	81.2	29.40
12	28.1	8.53	80.7	29.22
13	28.0	8.50	81.1	29.37
14	28.0	8.50	81.2	29.40
15	27.9	8.47	80.0	29.00
16	27.9	8.47	81.2	29.40
17	28.0	8.50	80.6	29.19
18	28.0	8.50	80.8	29.26
19	28.4	8.62	80.5	29.15
20	28.5	8.65	81.4	29.47

Table 2.- Alphabetical List of the Chondrites Investigated Including a Column With the Metallic Nickel-Iron Contents

No.+	Name	Metallic nickel-iron, weight %	Reference
24	Akron*	---	---
61	Albareto	5.23	Gallitelli [1939]**
67	Alfianello	6.79	Keil [1962]
7	Allegan	23.05	Merrill and Stokes [1900]**
25	Archie	---	---
68	Arriba*	---	---
15	Assisi	---	---
66	Ausson	---	---
46	Aztec	---	---
40	Bald Mountain	---	---
19	Barbotan	---	---
10	Bath	17.09	Keil [1962]
63	Bath Furnace	5.40	Keil [1962]
59	Baxter	---	---
26	Beardsley	---	---
27	Beaver Creek	17.68	Howell,et al. [1894]**
77	Bjurböle	7.69	Ramsay and Borgström [1902]**
56	Blanket	---	---
73	Brady	---	---
9	Breitscheid	17.71	Vilcsek [1959]
70	Bruderheim	8.25	Duke, et al. [1961]
36	Bushnel*	---	---
34	Butsura	18.47	Keil [1962]
51	Calliham*	---	---
57	Chantonnay	6.70	Keil [1962]
20	Charsonville	---	---
58	Chateau Renard	6.33	Keil [1962]
82	Cherokee Springs	---	---
47	Colby (Wisconsin)	---	---
22	Collescipoli	19.96	Wahl [Wiik] [1950a]**
72	Coon Butte*	9.25	Mallet [1906]**
14	Cosina	---	---
81	Dhurmsala	2.96	Keil [1962]
31	Djati-Pengilon	15.75	Keil [1962]
21	Dokachi	---	---
33	Ehole	---	---
32	Ekeby	18.66	Hadding [1940]**
49	Eli-Elwah*	6.24	Keil [1962]
54	Ergheo	1.56	Keil [1962]
28	Estacado*	16.02	Keil [1962]
52	Farmington	7.63	Keil [1962]
13	Florence	---	---
29	Forest City	21.06	Kunz [Eakins] [1890]**
50	Forksville	7.55	Merrill [Shannon] [1927]**

Table 2.- Alphabetical List of the Chondrites Investigated Including a Column With the Metallic Nickel-Iron Contents - Concluded

No.+	Name	Metallic nickel-iron, weight %	References
38	Fukutomi	10.83	Keil [1962]
75	Futtehpur	---	---
78	Girgenti	6.21	Keil [1962]
79	Harleton	8.51	Clarke [1962]
55	Harrisonville*	4.40	Keil [1962]
11	Hedeskoga	---	---
16	Hessle	18.98	Nordenskiold [Lindstrom] [1870]**
43	Hökmark	---	---
74	Holbrook	8.33	Mason and Wiik [1961]
42	Homestead	10.99	Prior [1918]**
41	Johnson City*	---	---
64	Kandahar	---	---
86	Kernouve	15.87	Keil [1962]
1	Kesen	---	---
65	Knyahinya	4.73	Keil [1962]
62	Kuttipuram	---	---
48	Kyushu	6.74	Keil [1962]
44	Ladder Creek	---	---
45	L'Aigle	11.65	Keil [1962]
5	Menow	16.46	Keil [1962]
3	Merua	20.10	Tipper [1925]**
80	Mocs	5.85	Keil [1962]
12	Monroe	---	---
39	Mooresfort	7.62	Keil [1962]
60	New Concord	8.22	Keil [1962]
30	Oakley*	14.63	Keil [1962]
83	Oberlin*	---	---
8	Ochansk	20.82	Wiik [1956]
23	Pultusk	16.55	Keil [1962]
37	Ramsdorf	---	---
2	Richardton	---	---
69	Saint Michel	9.13	Borgström [1912]**
84	Soko-Banja	4.32	Prior [1916b]**
6	Ställdalen	20.79	Lindstrom [1877]**
4	Tabor	16.90	Keil [1962]
53	Taiban*	---	---
71	Temple*	---	---
18	Tomhannock Creek*	16.00	Keil [1962]
17	Tulia*	---	---
85	Varvik*,***	---	---
76	Walters*	---	---
35	Zhovtnevyi	17.66	Keil [1962]

Footnotes to Table 2:

+Number in column one refers to Table 3.

*Meteorites are finds.

**'Superior' chemical analyses according to Urey and Craig [1953].

***This meteorite is listed as Näs in Prior-Hey [1953]. This very fresh and unaltered-looking chondrite has been classified as a find, however, a meteorite fall was observed in this area on May 14, 1907. It seems likely that the stone Vårvik, which was found some time thereafter, might have fallen at this particular date.

Table 3.- Composition of Coexisting Olivine and Rhombic Pyroxene in 86 Chondrites

No.	Name	Classification in LL-, L-, and H-groups	Olivine			Rhombic pyroxene			
			Weight %		Mol % Fe	Weight %			Mol % Fe
			Fe	Mg	Fe + Mg	Fe	Mg	Ca	Fe + Mg
1	Kesen	H	11.9	27.1	16.1	7.7	19.0	0.40	15.0
2	Richardton	H	12.1	27.3	16.2	7.7	19.4	.27	14.7
3	Merua	H	12.2	26.8	16.5	8.0	18.7	.33	15.7
4	Tabor	H	12.2	26.8	16.5	7.8	18.8	.32	15.3
5	Menow	H	12.9	26.7	17.4	8.0	18.4	.53	15.9
6	Ställdalen	H	13.0	26.3	17.7	8.4	19.2	.38	16.0
7	Allegan	H	13.0	26.6	17.5	8.5	19.4	.37	16.0
8	Ochansk	H	13.0	26.7	17.5	8.2	19.3	.33	15.6
9	Breitscheid	H	13.0	26.8	17.4	8.3	18.8	.40	16.1
10	Bath	H	13.1	26.4	17.8	8.0	18.7	.40	15.7
11	Hedeskoga	H	13.1	26.7	17.6	8.7	18.8	.50	16.8
12	Monroe	H	13.1	26.7	17.6	8.2	19.1	.23	15.8
13	Florence	H	13.1	26.8	17.6	8.3	18.6	.68	16.3
14	Cosina	H	13.1	27.4	17.2	8.3	19.5	.43	15.8
15	Assisi	H	13.2	26.4	17.9	8.6	19.6	.42	16.0
16	Hessle	H	13.2	26.6	17.8	8.2	18.6	.42	16.1
17	Tulia*	H	13.3	26.5	17.9	8.6	19.0	.30	16.5
18	Tomhannock Creek*	H	13.3	26.5	17.9	8.4	18.8	.47	16.3
19	Barbotan	H	13.3	26.5	17.9	8.3	19.0	.39	16.0
20	Charsonville	H	13.3	26.8	17.8	8.7	19.0	.53	16.6
21	Dokachi	H	13.4	26.6	18.0	8.4	18.7	.46	16.4
22	Collescipoli	H	13.4	26.8	17.8	8.6	19.3	.41	16.3
23	Pultusk	H	13.5	26.4	18.2	8.1	19.1	.30	15.6
24	Akron*	H	13.5	26.7	18.0	8.5	18.8	.46	16.5
25	Archie	H	13.5	26.7	18.0	8.5	18.7	.51	16.5
26	Beardsley	H	13.6	26.0	18.6	8.2	18.3	.45	16.3
27	Beaver Creek	H	13.6	26.4	18.3	8.3	19.0	.48	16.0
28	Estacado*	H	13.7	26.4	18.4	8.5	18.6	.35	16.6
29	Forest City	H	13.7	26.6	18.3	8.3	19.0	.40	16.0
30	Oakley*	H	13.7	26.6	18.3	8.7	18.8	.63	16.8
31	Djati-Pengilon	H	13.8	26.2	18.7	8.7	18.7	.40	16.8
32	Ekeby	H	13.9	25.9	18.9	8.6	18.5	.38	16.8
33	Ehole	H	14.0	26.0	19.0	8.6	18.7	.41	16.7
34	Butsura	H	14.0	27.1	18.4	8.8	19.1	.51	16.7
35	Zhovtnevyi	H	14.1	26.2	19.0	8.7	19.0	.37	16.6
36	Bushnel*	H	14.3	25.8	19.4	8.8	18.4	.42	17.2
37	Ramsdorf	L	15.8	24.9	21.6	9.0	18.0	1.1	17.9
38	Fukutomi	L	15.9	25.1	21.6	10.0	17.7	.34	19.7
39	Mooresfort	L	16.0	24.4	22.2	10.0	17.5	.42	19.9
40	Bald Mountain	L	16.1	24.8	22.0	9.8	17.9	.29	19.3
41	Johnson City	L	16.3	24.2	22.7	9.9	17.2	.54	20.0
42	Homestead**	L	16.3	25.1	22.0	10.3	18.1	.45	19.9

Table 3.- Composition of Coexisting Olivine and Rhombic Pyroxene in 86 Chondrites - Concluded

No.	Name	Classification in LL-, L-, and H-groups	Olivine			Rhombic pyroxene			
			Weight %		Mol % Fe / Fe + Mg	Weight %			Mol % Fe / Fe + Mg
			Fe	Mg		Fe	Mg	Ca	
43	Hökmark	L	16.5	24.5	22.7	9.8	17.5	0.36	19.6
44	Ladder Creek*	L	16.5	24.6	22.6	10.5	17.2	.65	21.0
45	L'Aigle	L	16.7	24.5	22.9	10.0	17.5	.54	19.9
46	Aztec	L	16.8	24.7	22.9	10.2	17.9	.64	19.9
47	Colby (Wisconsin)	L	17.0	24.2	23.4	10.5	17.4	.30	20.8
48	Kyushu	L	17.0	24.4	23.3	10.4	17.4	.49	20.6
49	Eli-Elwah	L	17.1	24.2	23.5	10.7	17.8	.34	20.7
50	Forksville	L	17.2	23.9	23.9	10.4	17.2	.60	20.8
51	Calliham*	L	17.2	24.0	23.8	10.7	17.2	.62	21.3
52	Farmington	L	17.2	24.0	23.8	10.3	17.4	.57	20.5
53	Taiban*	L	17.2	24.0	23.8	10.8	17.4	.45	21.3
54	Ergheo	L	17.2	24.1	23.7	10.5	17.7	.36	20.5
55	Harrisonville*	L	17.2	24.2	23.6	10.4	17.4	.63	20.6
56	Blanket	L	17.2	24.4	23.5	10.7	17.7	.46	20.8
57	Chantonnay	L	17.2	24.7	23.3	10.4	17.6	.53	20.5
58	Chateau Renard	L	17.3	24.3	23.7	10.3	17.4	.56	20.5
59	Baxter	L	17.3	24.4	23.6	10.7	17.7	.63	20.8
60	New Concord	L	17.3	24.4	23.6	10.4	17.7	.46	20.4
61	Albareto	L	17.4	23.5	24.4	10.6	16.7	.40	21.7
62	Kuttipuram	L	17.4	23.8	24.1	10.5	17.5	.59	20.7
63	Bath Furnace	L	17.4	24.0	24.0	10.4	17.3	.52	20.7
64	Kandahar	L	17.4	24.2	23.8	10.4	17.7	.45	20.4
65	Knyahinya	L	17.4	24.2	23.8	10.6	17.5	.54	20.9
66	Aussun	L	17.4	24.3	23.8	10.6	17.6	.49	20.8
67	Alfianello	L	17.4	24.4	23.7	10.6	17.5	.65	20.9
68	Arriba*	L	17.5	23.9	24.2	10.7	17.2	.43	21.3
69	Saint Michel	L	17.5	24.2	23.9	10.8	17.5	.55	21.2
70	Bruderheim	L	17.5	24.4	23.8	10.9	18.2	.39	20.7
71	Temple*,***	L	17.7	23.8	24.5	10.7	17.5	.47	21.0
72	Coon Butte*	L	17.7	24.0	24.3	10.6	17.6	.54	20.8
73	Brady*	L	17.7	24.3	24.1	10.5	17.9	.65	20.3
74	Holbrook	L	17.8	23.8	24.6	10.5	17.4	.60	20.8
75	Futtehpur	L	17.8	24.2	24.3	10.5	17.4	.51	20.8
76	Walters*	L	17.8	24.0	24.4	10.7	17.4	.52	21.1
77	Bjurböle	L	17.8	23.9	24.5	10.8	17.5	.34	21.2
78	Girgenti	L	17.8	24.2	24.3	10.9	17.7	.47	21.1
79	Harleton	L	17.8	24.4	24.1	10.8	18.0	.55	20.7
80	Mocs	L	17.9	24.1	24.4	10.5	17.4	.46	20.8
81	Dhurmsala	LL	19.0	23.2	26.3	11.2	17.1	.60	22.2
82	Cherokee Springs	LL	19.5	22.7	27.2	11.5	17.0	.45	22.8
83	Oberlin*	LL	19.5	23.0	27.0	11.8	16.9	.46	23.3
84	Soko-Banja	LL	19.6	23.2	26.9	11.6	17.2	.36	22.7
85	Vårvik	LL	20.6	22.0	29.0	12.3	16.4	.62	24.6
86	Kernouve	H	No olivine found			8.5	18.8	.48	16.5

Footnotes to Table 3:

*Meteorites are finds.

**On the basis of the 'superior' analysis by Prior [1918], Urey and Craig [1953] classified the chondrite Homestead as belonging to the L-group. This is in agreement with the results of the X-ray diffraction analyses of the silicates (Mason, personal communication) and the electron microprobe analyses of coexisting olivines and rhombic pyroxenes (this paper).

According to the planimetric integration analyses of three large polished sections (total measured area 46.3 cm^2) from two collections (Mineralogical Institute, Humboldt University, Berlin, Germany, and Mineralogical Institute, University of Greifswald, Germany) this meteorite has recently been classified as a H-group chondrite [Keil, 1962a,b]. Since Homestead is classified as a polymict breccia [Prior and Hey, 1953], it is an intriguing thought that this meteorite might be a mixture of L- and H-group fragments. However, Mason's suggestion, that the Berlin and Greifswald sections might be mislabeled pieces of some other chondrites, should be considered as a likely explanation (Mason, personal communication).

***The stone meteorite Temple has formerly been classified as being an achondrite (American Meteorite Laboratory, Denver, Colorado). However, the meteorite was found to be a typical L-group chondrite.

Table 4.- Average Composition of Olivine and Rhombic Pyroxene in LL-, L-, and H-Group Chondrites

Group	Number of chondrites	Olivine			Rhombic pyroxene			
		Weight %		Mol % $\frac{Fe}{Fe + Mg}$	Weight %			Mol % $\frac{Fe}{Fe + Mg}$
		Fe	Mg		Fe	Mg	Ca	
LL	5	19.6	22.8	27.3	11.7	16.9	0.50	23.1
L	44	17.2	24.3	23.6	10.4	17.6	.50	20.5
H	36	13.3	26.6	17.9	8.4	18.9	.42	16.2
Total chondrites	85	15.7	25.1	21.4	9.6	18.1	.47	18.9

Table 5.- Classification of Chondrites into LL-, L-, and H-Groups on the Basis of Chemical-Mineralogical Parameters

Classification	LL-Group A: Average B: Range in composition	L-Group A: Average B: Range in composition	H-Group A: Average B: Range in composition	References
Bulk iron, on the basis of 'superior' bulk chemical analyses (weight %)	A. 20.87 (7) B. 19.85-22.55	A. 21.82 (30) B. 20.55-23.33	A. 27.52 (27) B. 25.34-30.88	Craig (in press)
Ratio $\frac{Fe}{Ni}$ in metallic nickel-iron, on the basis of 'superior' chemical analyses	A. 3.57 (7)	A. 6.87 (30)	A. 10.90 (27)	Craig (in press)
Metallic nickel-iron, on the basis of planimetric integration analyses of polished sections (weight %)	A. 2.64 (3)* B. 1.72-3.23	A. 6.85 (38)** B. 4.40-11.65	A. 16.72 (28)*** B. 14.17-19.81	Keil [1962a,b]
Ratio $\frac{Fe}{Fe + Mg}$ in olivine (mol %)	A. 27.3 (5) B. 29.0-26.3	A. 23.6 (44) B. 24.6-21.6	A. 17.9 (36) B. 19.4-16.1	This paper
Ratio $\frac{Fe}{Fe + Mg}$ in rhombic pyroxene (mol %)	A. 23.1 (5) B. 24.6-22.2	A. 20.5 (44) B. 21.7-17.9	A. 16.2 (36) B. 17.2-14.7	This paper
Specific gravity	A. 3.48+ (10) B. 3.44-3.54	A. 3.52 (87) B. 3.26-3.75	A. 3.69++ (62) B. 3.50-3.90	Based on Pokrzywnicki [1959] and Keil [1962b]

NOTE: The number of chondrites measured and included in the averages are given in parentheses.

Footnotes to Table 5:

*The chondrites Dhurmsala, Ensisheim, and Mainz, formerly classified into the L-group [Keil, 1962a,b] have been included in the average for the LL-group. According to the metallic nickel-iron content and to the $\frac{Fe}{Fe + Mg}$ ratios in olivine and rhombic pyroxene, the Dhurmsala-meteorite is a typical LL-group chondrite. However, the classification of the Ensisheim and Mainz chondrites into the LL-group is somewhat uncertain, since it is only based on one parameter, namely, the metallic nickel-iron content.

**The average includes the low value (1.56%) of the Ergheo chondrite. This meteorite was picked up five years after the fall and, therefore, is considerably weathered. The low metallic nickel-iron value may well be due to this effect; however, the microprobe analyses of olivine and rhombic pyroxene in this meteorite confirm its classification into the L-group.

***Excluded from this average are the chondrites Hvittis, Pillistfer, and Lance, since they belong to separate groups (enstatite chondrites and ornansites, respectively). In addition, the chondrite Homestead has been excluded from the average, since the slabs investigated were probably mislabeled (cf. footnote to Table 3).

+From this average, the doubtful value of the chondrite Guidder (3.92) has been excluded.

++From this average, the doubtful values of the chondrites Bowden (3.39), Cosina (3.10), and Hedeskoga (3.17) have been excluded.

Table 6.- Comparison of the Mol Per Cent Ratios $\frac{Fe}{Fe + Mg}$ as Calculated From FeO and MgO of 'Superior' Bulk Chemical Analyses With the $\frac{Fe}{Fe + Mg}$ Ratios in Olivine and Rhombic Pyroxene as Obtained by Microprobe Analyses

No.+	Name	Group	This paper		Chemical analyses	Reference
			Mol % ratios $\frac{Fe}{Fe + Mg}$		Mol % ratios $\frac{Fe}{Fe + Mg}$ as calculated from FeO and MgO of bulk chemical analyses	
			Olivine	Rhombic pyroxene		
3	Merua	H	16.5	15.7	15.3	Tipper [1925]**
9	Breitscheid	H	17.4	16.1	14.8	Vilcsek [1959]
8	Ochansk	H	17.5	15.6	14.4	Wiik [1956]
7	Allegan	H	17.5	16.0	17.8	Merrill and Stokes [1900]**
6	Ställdalen	H	17.7	16.0	16.5	Lindstrom [1877]**
16	Hessle	H	17.8	16.1	20.8	Nordenskiold [Lindstrom] [1870]**
22	Collescipoli	H	17.8	16.3	12.4	Wahl [Wiik] [1950a**]
18	Tomhannock Creek*	H	17.9	16.3	26.0	Mason and Wiik [1960]
27	Beaver Creek	H	18.3	16.0	19.4	Howell, et al. [1894]**
29	Forest City	H	18.3	16.0	16.0	Kunz [Eakins] [1890]**
30	Oakley*	H	18.3	16.8	19.6	Wahl [Wiik] [1950b]**
28	Estacado*	H	18.4	16.6	23.5	Howard and Davison [1906]**
31	Djati-Pengilon	H	18.7	16.8	26.8	Daubree [Retgers] [1887]**
32	Ekeby	H	18.9	16.8	21.0	Hadding [1940]**
42	Homestead	L	22.0	19.9	21.9	Prior [1918]**
57	Chantonnay	L	23.3	20.5	24.9	Rammelsberg [1870]**
48	Kyushu	L	23.3	20.6	26.0	Mason and Wiik [1961a]
60	New Concord	L	23.6	20.4	20.9	Mason and Wiik [1961b]
58	Chateau Renard	L	23.7	20.5	21.9	Mason and Wiik [1961b]
70	Bruderheim	L	23.8	20.7	24.0	Duke, et al. [1961]
50	Forksville	L	23.9	20.8	28.4	Merrill [Shannon] [1927]**
69	Saint Michel	L	23.9	21.2	23.5	Borgström [1912]**
79	Harleton	L	24.1	20.7	29.8	Clarke [1962]
72	Coon Butte*	L	24.3	20.8	24.7	Mallet [1906]**

Table 6.- Comparison of the Mol Per Cent Ratios $\frac{Fe}{Fe + Mg}$ as Calculated From FeO and MgO of 'Superior' Bulk Chemical Analyses With the $\frac{Fe}{Fe + Mg}$ Ratios in Olivine and Rhombic Pyroxene as Obtained by Microprobe Analyses - Concluded

No.+	Name	Group	This paper: Mol % ratios $\frac{Fe}{Fe + Mg}$		Chemical analyses: Mol % ratios $\frac{Fe}{Fe + Mg}$ as calculated from FeO and MgO of bulk chemical analyses	References
			Olivine	Rhombic pyroxene		
78	Girgenti	L	24.3	21.1	27.7	v. Rath [1869]**
80	Mocs	L	24.4	20.8	20.9	Mason and Wiik [1961b]
61	Albareto	L	24.4	21.7	25.8	Gallitelli [1939]**
77	Bjurböle	L	24.5	21.2	22.3	Ramsay and Borgstrom [1902]**
74	Holbrook	L	24.6	20.8	20.8	Mason and Wiik [1961c]
84	Soko-Banja	LL	26.9	22.7	28.0	Prior [1916b]**
86	Kernouve	H	---	16.5	21.7	Pisani [1869]**

+Number in column one refers to Table 3.
*Meteorites are finds.
**'Superior' chemical analyses according to Urey and Craig [1953].

Table 7.- Chondrite Bjurböle. Average composition of 84 Olivine Crystals From 17 Individual Chondrules and 15 Rhombic Pyroxene Crystals From 6 Individual Chondrules

Olivine			Rhombic pyroxene			
Weight %		Mol % $\frac{Fe}{Fe+Mg}$	Weight %			Mol % $\frac{Fe}{Fe+Mg}$
Fe	Mg		Fe	Mg	Ca	
17.8±0.2	23.9±0.2	24.5±0.3	10.8±0.4	17.5±0.3	0.34±0.1	21.2±0.3

Table 8.- Chondrites Containing Olivines and Pyroxenes With Varying Composition

Name	Olivine			Pyroxene			
	Weight %		Mol % $\frac{Fe}{Fe + Mg}$	Weight %			Mol % $\frac{Fe}{Fe + Mg}$
	Fe	Mg		Fe	Mg	Ca	
Bishunpur	14.6	25.5	20.0	12.0 14.9	16.6 14.9	0.35 .35	23.9 30.3
Bremervörde	12.9	26.8	17.3	3.4-8.7 8.4 11.0	21.2-18.5 18.6 16.5	0.52-0.64 0.74 .94	6.5-17.0 16.4 22.5
Castalia	13.3 13.8 15.6	26.2 26.8 25.5	18.1 18.3 21.0	6.3 8.6 10.4	20.6 19.0 17.7	.14 .44 .39	11.8 16.5 20.4
Khohar	5.1 14.3 16.6 17.6 18.2	31.7 26.3 24.9 24.2 23.9	6.5 19.1 22.5 24.0 24.9	2.7 8.9 9.9	21.3 18.6 17.7	.24 .55 .59	5.2 17.2 19.6
Lua	13.5 15.0 16.0 16.8	26.7 25.9 25.3 25.0	18.0 20.1 21.6 22.6	3.0	22.4	.32	5.5

Table 8.- Chondrites Containing Olivines and Pyroxenes With Varying Composition - Continued

Name	Olivine			Pyroxene			
	Weight %		Mol % $\frac{Fe}{Fe + Mg}$	Weight %			Mol % $\frac{Fe}{Fe + Mg}$
	Fe	Mg		Fe	Mg	Ca	
Mezö-Madras	11.7	27.6	15.6	9.2	18.7	0.10	17.7
	15.6	25.2	21.2	9.6	18.0	.23	18.8
	15.7	24.8	21.6	13.8	11.9	.80	33.6
	15.7	25.2	21.3				
	15.8	25.0	21.6				
	15.8	25.1	21.5				
	15.9	24.9	21.8				
	15.9	25.1	21.6				
	15.9	25.2	21.6				
	16.2	24.9	22.1				
	16.6	24.8	22.6				
	17.9	23.8	24.7				
	17.9	23.9	24.6				
	20.5	20.9	29.9				
Prairie Dog Creek	10.6	27.7	14.3	5.8-6.9	20.3-20.0	.15	11.1-13.1
	13.1	26.3	17.8	6.1	20.2	.44	11.6
	13.1	26.6	17.7	9.0	18.7	.22	17.3
	13.2	26.0	18.1	14.1	15.1	.47	28.9
	13.3	26.1	18.2				
	13.3	26.4	18.0				
	13.5	26.3	18.3				
	13.6	26.1	18.5				
	13.6	26.3	18.4				
	13.7	25.9	18.7				

Table 8.- Chondrites Containing Olivines and Pyroxenes With Varying Composition - Concluded

Name	Olivine			Pyroxene			
	Weight %		Mol % $\frac{Fe}{Fe + Mg}$	Weight %			Mol % $\frac{Fe}{Fe + Mg}$
	Fe	Mg		Fe	Mg	Ca	
Sindhri	4.6	31.3	6.0	1.9	23.0	0.19	3.5
	5.2	31.1	6.8	2.0	22.7	.10	3.7
	9.7	28.9	12.8	2.9	21.8	.20	5.5
	10.4-13.1	28.7-27.7	13.6-17.1	2.9	22.2	.17	5.4
	10.6	28.5	13.9	3.5	21.0	.20	6.8
	11.2	28.0	15.0	4.7	21.2	.20	8.8
	11.4	28.2	15.0	5.3	21.3	.10	9.8
	11.8	27.9	15.6	5.8	20.5	.29	11.0
	11.9	27.6	15.8	6.5	20.3	.28	12.2
	12.2	27.3	16.3	7.6	19.4	.10	14.6
	12.8	27.0	17.1	8.4	18.9	.38	16.2
	13.2	26.8	17.7	8.4	19.0	.44	16.1
	13.3	26.4	18.0	8.4	19.2	.36	16.0
	13.3	26.4	18.0	8.5	18.8	.51	16.5
	13.3	26.7	17.8	8.5	19.0	.47	16.3
	13.3	26.9	17.7	9.1	18.5	.38	17.6
	13.3	27.3	17.5	10.4	17.9	.16	20.2
	13.3	27.6	17.3	12.2	16.9	.75	23.9
	13.6	27.1	17.9				
	13.7	26.9	18.2				
	13.7	27.2	18.0				
	13.8	26.8	18.3				
	13.8	26.8	18.3				
	13.9	26.6	18.5				
	14.2	26.9	18.7				
	14.6	26.5	19.3				
	15.2	26.0	20.3				
	15.2	26.0	20.3				

FIGURE TITLES

Figure 1.- Calibration curves for Fe and Mg in olivine.

Figure 2.- Calculated calibration curves for Fe and Mg in rhombic pyroxene.

Figure 3.- Chondrite Bjurböle. Frequency distribution of the mol per cent ratios $\frac{Fe}{Fe + Mg}$ in olivine. Eighty-four analyzed individual olivine crystals from seventeen different chondrules, average $24.5 \pm 0.2_6$.

Figure 4.- Ratios $\frac{Fe}{Fe + Mg}$ in olivine plotted against ratios $\frac{Fe}{Fe + Mg}$ in rhombic pyroxene for the chondrites listed in Table 3 (in mol per cent).

Figure 5.- Frequency distribution of the ratios $\frac{\left(\frac{Fe}{Fe + Mg}\right)_{olivine}}{\left(\frac{Fe}{Fe + Mg}\right)_{rh.\ pyroxene}}$ for the chondrites listed in Table 3.

Figure 6.- The difference $\left(\frac{Fe}{Fe + Mg}\right)_{olivine}$ minus $\left(\frac{Fe}{Fe + Mg}\right)_{rh.\ pyroxene}$ in chondrites increases with increasing oxidized iron.

Figure 7.- Frequency distribution of the mol per cent ratios $\frac{Fe}{Fe + Mg}$ in olivine for the chondrites listed in Table 3.

Figure 8.- Frequency distribution of the mol per cent ratios $\frac{Fe}{Fe + Mg}$ in rhombic pyroxene for the chondrites listed in Table 3.

Figure 9.- Frequency distribution of the calcium content of rhombic pyroxenes in the chondrites listed in Table 3.

Figure 10.- Calcium content in the rhombic pyroxenes of the chondrites listed in Table 3.

Figure 11.- Relation between the amount of metallic nickel-iron and oxidized iron in olivine and rhombic pyroxene. The metallic nickel-iron values of chondrites, symbolized by crosses, were obtained from papers by Keil [1962a,b]; the values symbolized by circles were obtained from 'superior' chemical analyses of several sources (cf. Table 2).

Figure 12.- Mol per cent ratios $\frac{Fe}{Fe + Mg}$ as calculated from FeO and MgO of 'superior' bulk chemical analyses versus ratios $\frac{Fe}{Fe + Mg}$ in olivine and rhombic pyroxene of chondrites obtained by microprobe analyses.

Figure 13.- Chondrite Chainpur. Composition of individual pyroxene crystals from individual chondrules, plotted in $MgSiO_3$-$FeSiO_3$-$CaSiO_3$ concentration triangles.

Figure 14.- Carbonaceous chondrite Murray. Frequency distribution of the mol per cent ratios $\frac{Fe}{Fe + Mg}$ in 63 individual olivine crystals.

Figure 15.- Phase relations of 1550°C in the MgO-FeO-SiO_2 system after Bowen and Schairer [1935]. L_{sil} and H_{sil} show average MgO, FeO, and SiO_2 for L- and H-group chondrites; H_{tot} and L_{tot} were calculated from these values by adding FeO corresponding to average metallic Fe contents; O_{tot} represents the carbonaceous chondrite Orgueil. H_{ol} and L_{ol} indicates average olivine compositions. The figure illustrates that more ferrous iron than now in the silicates was present during olivine crystallization. Note also that from H_{tot} to H_{sil} the melting point remains practically constant $\gtrsim$ 1550°C, for example, above the melting point of nickel-iron.

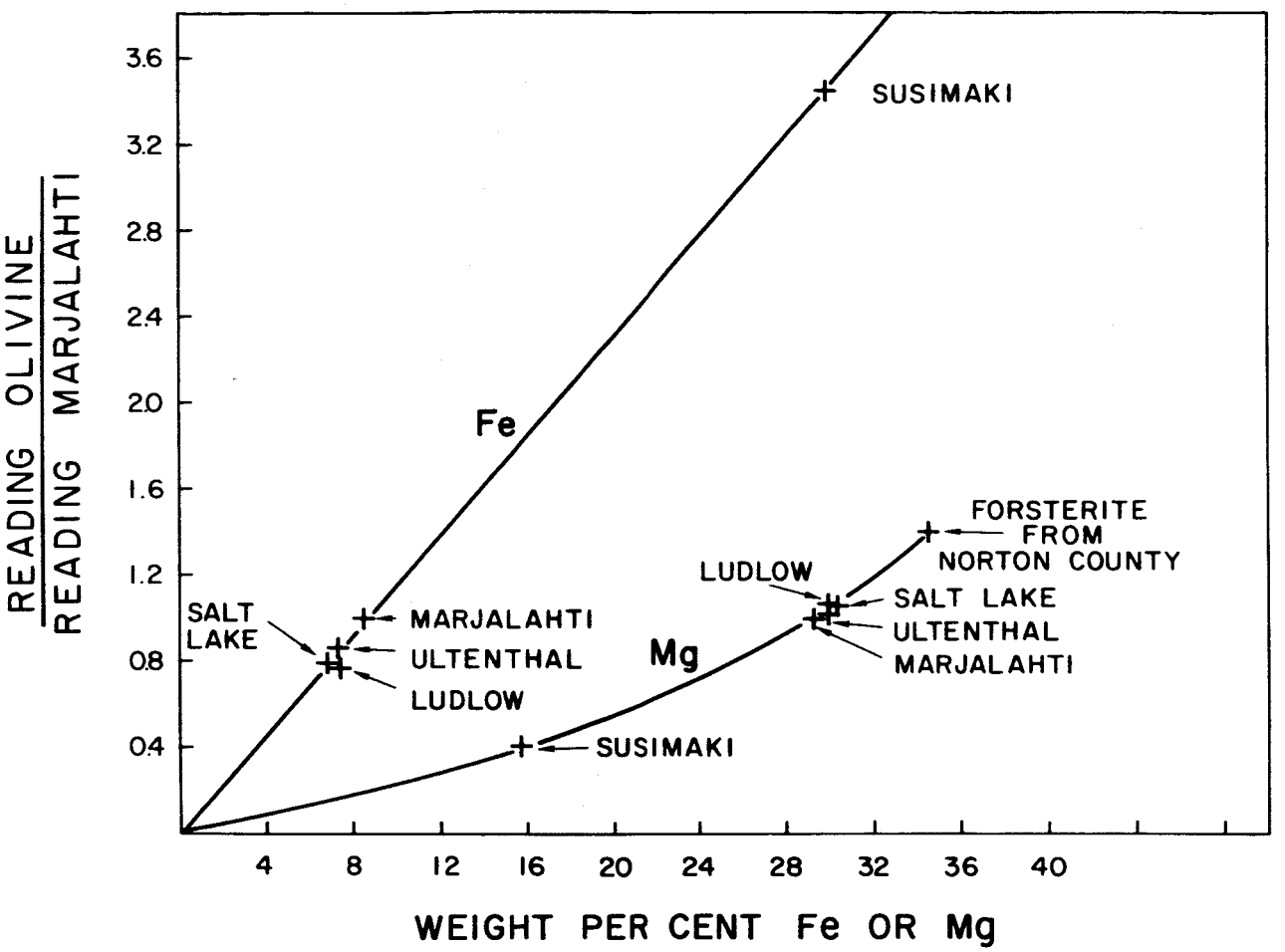


Figure 1.- Calibration curves for Fe and Mg in olivine.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
AMES RESEARCH CENTER, MOFFETT FIELD, CALIFORNIA

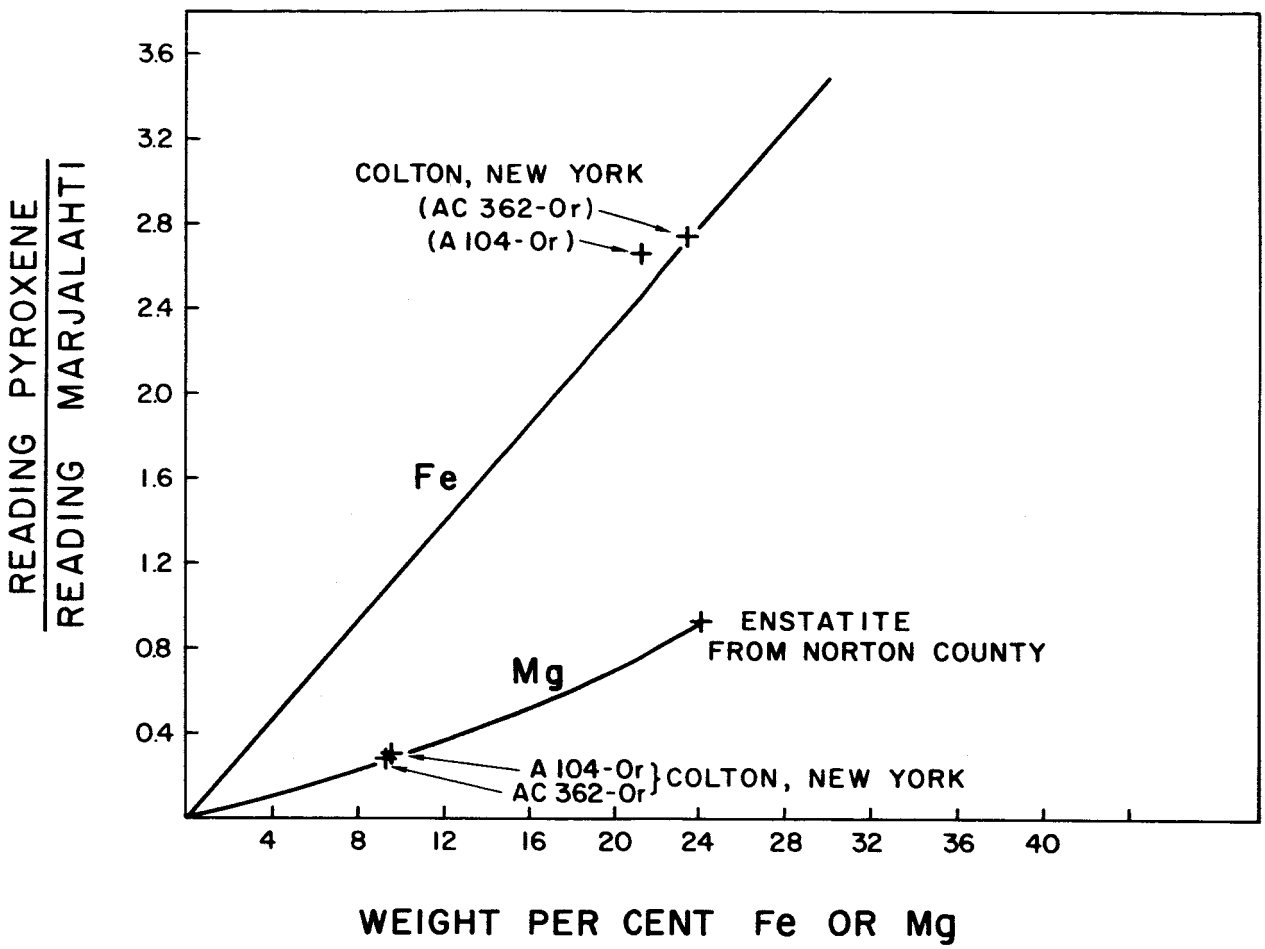


Figure 2.- Calculated calibration curves for Fe and Mg in rhombic pyroxene.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
AMES RESEARCH CENTER, MOFFETT FIELD, CALIFORNIA

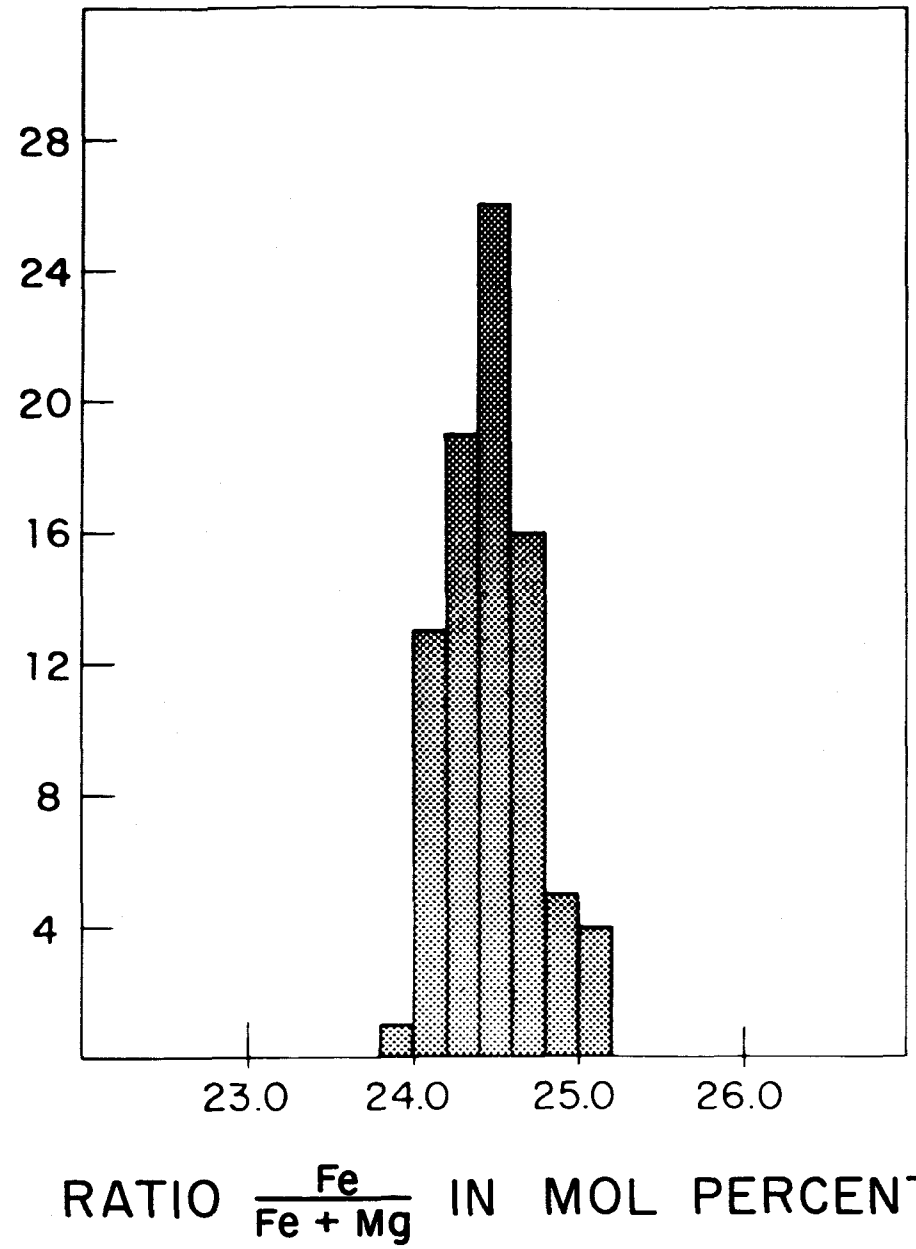


Figure 3.- Chondrite Bjurböle. Frequency distribution of the mol per cent ratios $\frac{Fe}{Fe + Mg}$ in olivine. Eighty-four analyzed individual olivine crystals from seventeen different chondrules; average $24.5 \pm 0.2_e$.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
AMES RESEARCH CENTER, MOFFETT FIELD, CALIFORNIA

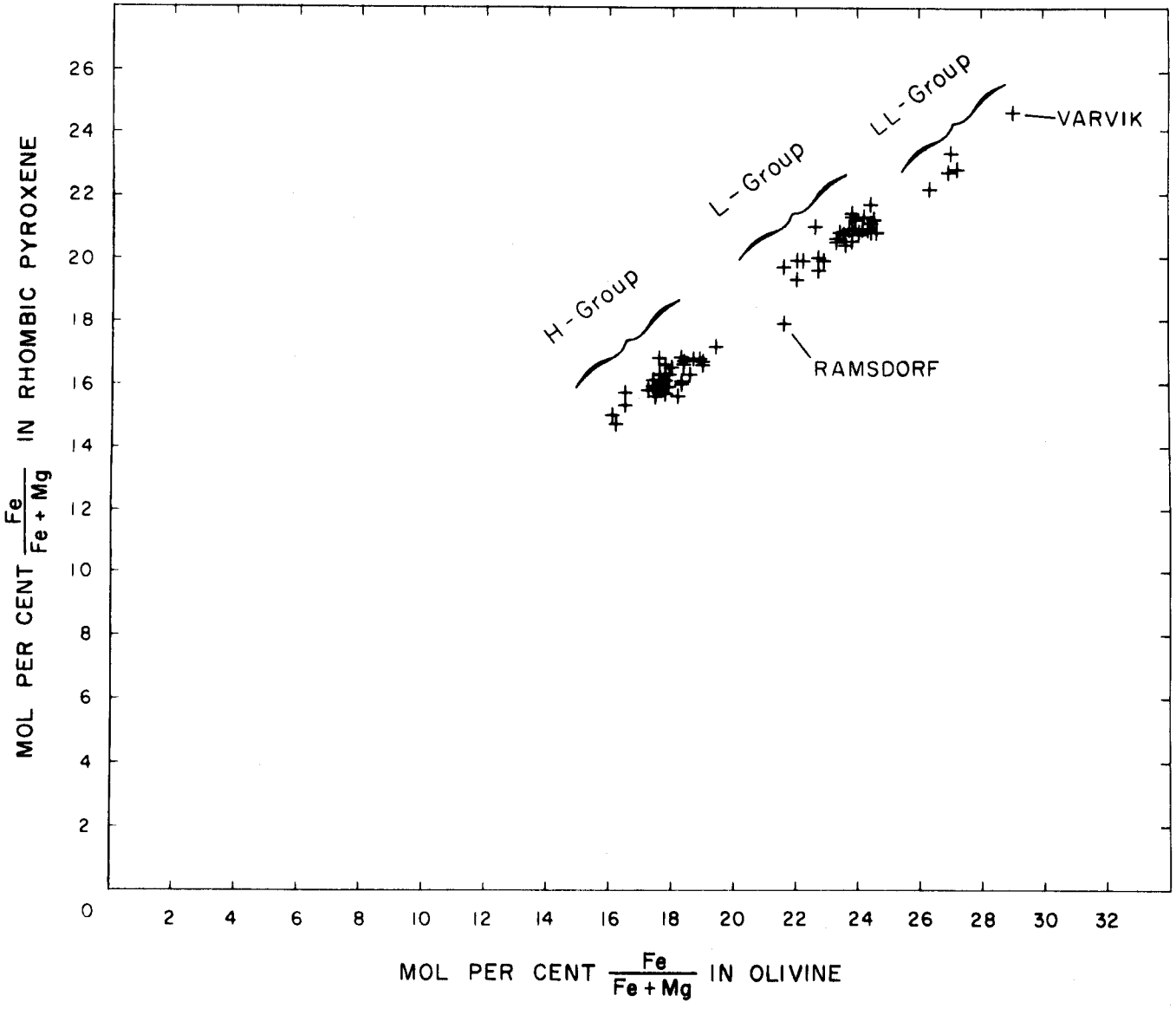


Figure 4.- Ratios $\frac{Fe}{Fe + Mg}$ in olivine plotted against ratios $\frac{Fe}{Fe + Mg}$ in rhombic pyroxene for the chondrites listed in Table 3 (in mol per cent).

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
AMES RESEARCH CENTER, MOFFETT FIELD, CALIFORNIA

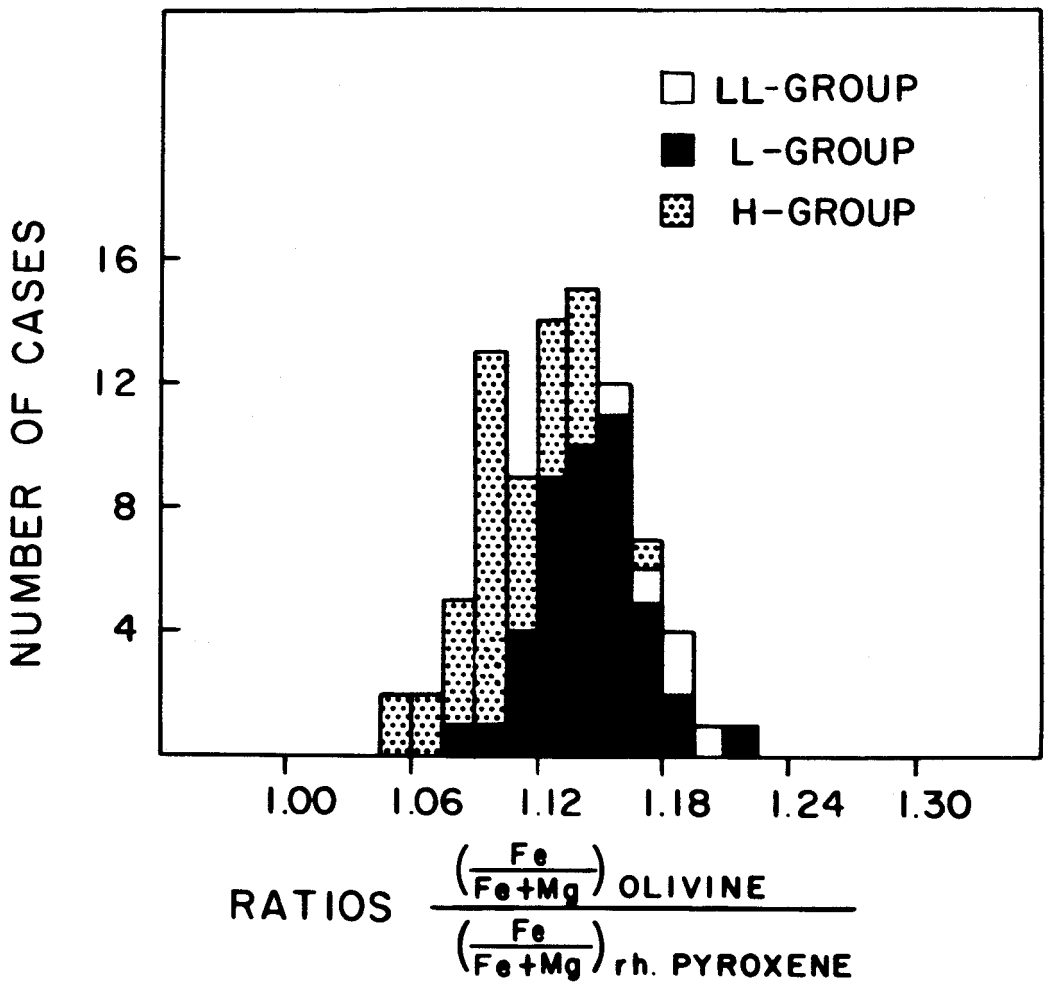


Figure 5.- Frequency distribution of the ratios $\frac{\left(\frac{Fe}{Fe + Mg}\right)_{olivine}}{\left(\frac{Fe}{Fe + Mg}\right)_{rh.\ pyroxene}}$ for the chondrites listed in Table 3.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
AMES RESEARCH CENTER, MOFFETT FIELD, CALIFORNIA

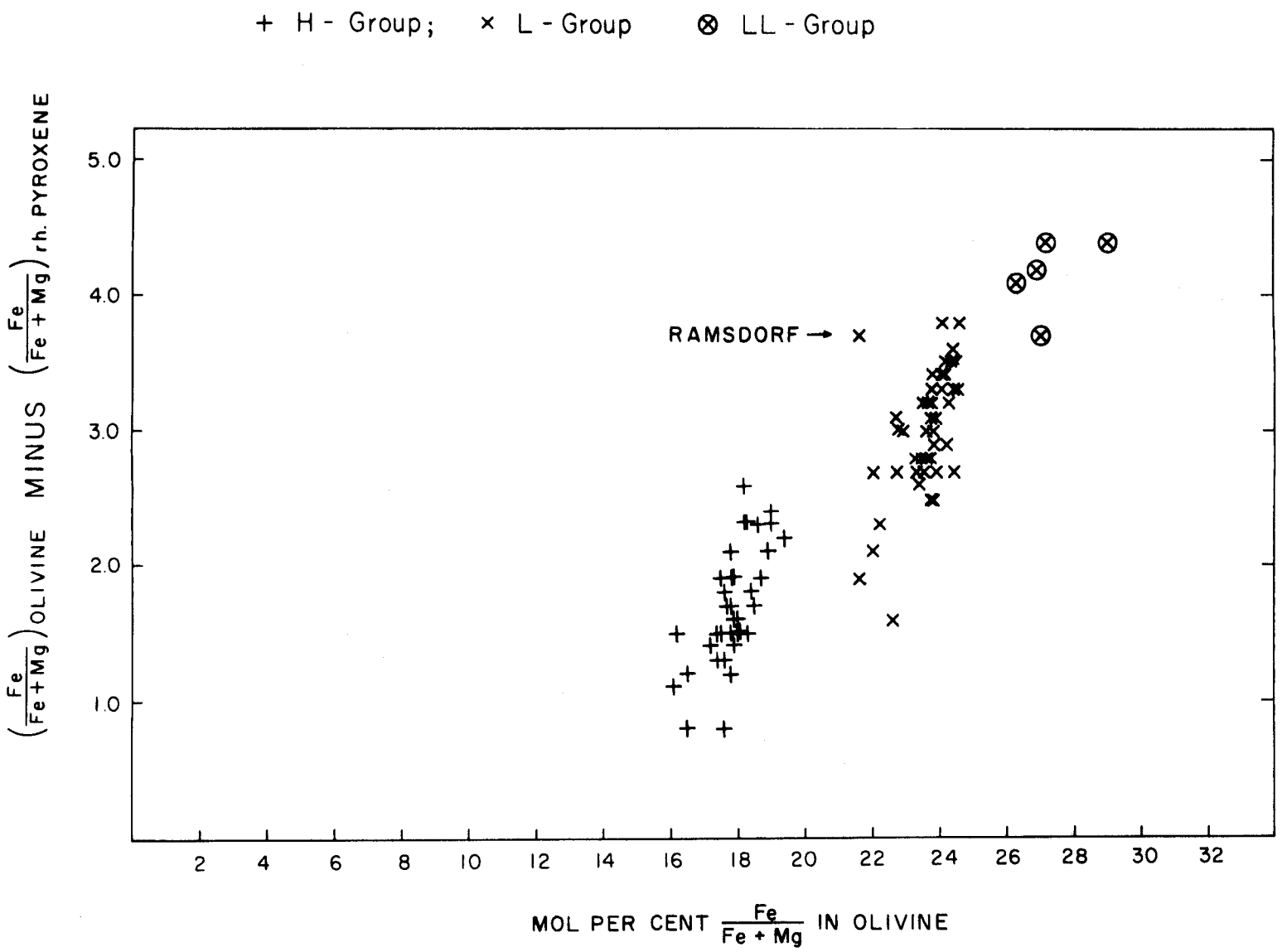


Figure 6.- The difference $\left(\frac{Fe}{Fe + Mg}\right)_{olivine}$ minus $\left(\frac{Fe}{Fe + Mg}\right)_{rh.\ pyroxene}$ in chondrites increases with increasing oxidized iron.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
AMES RESEARCH CENTER, MOFFETT FIELD, CALIFORNIA

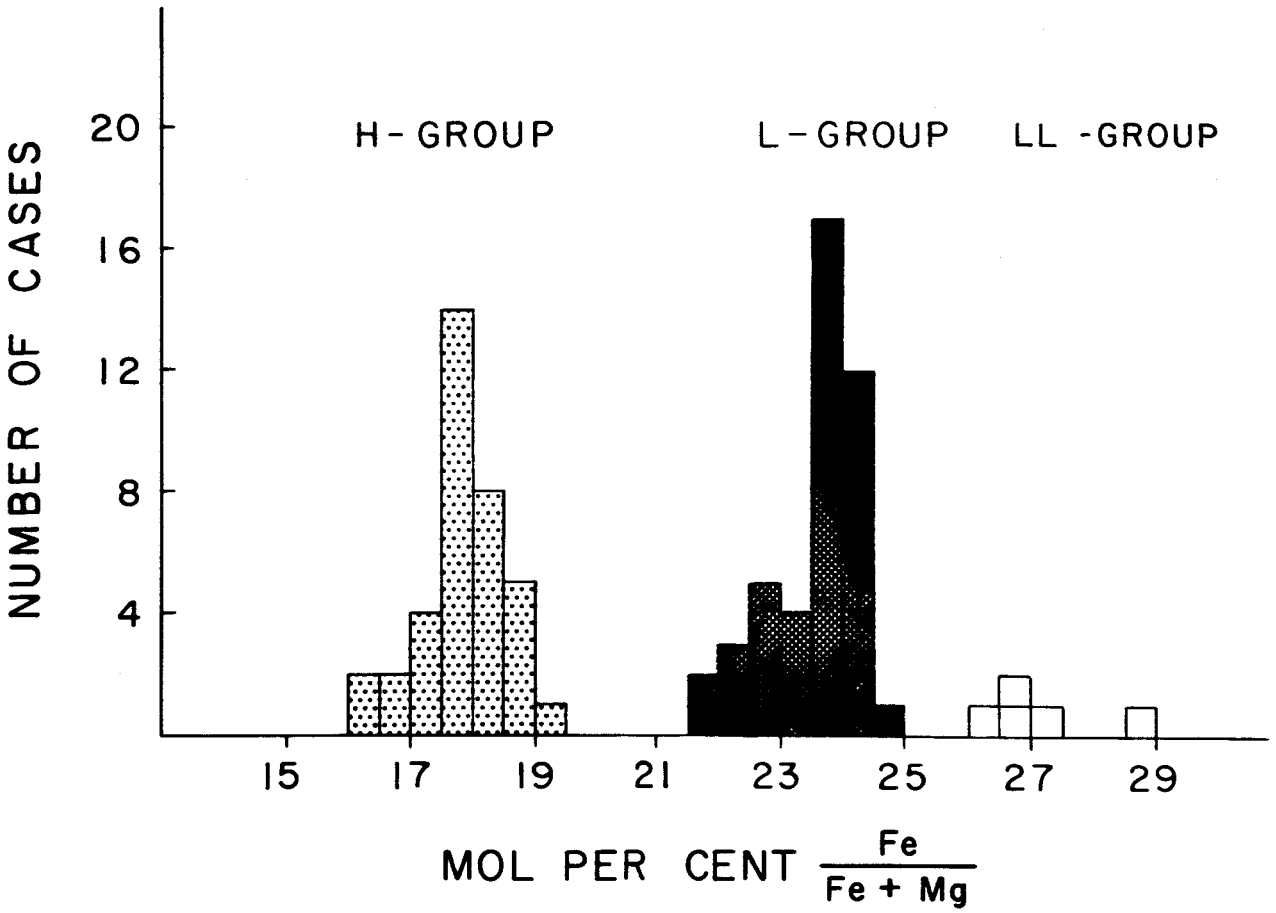


Figure 7.- Frequency distribution of the mol per cent ratios $\frac{Fe}{Fe + Mg}$ in olivine for the chondrites listed in Table 3.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
AMES RESEARCH CENTER, MOFFETT FIELD, CALIFORNIA

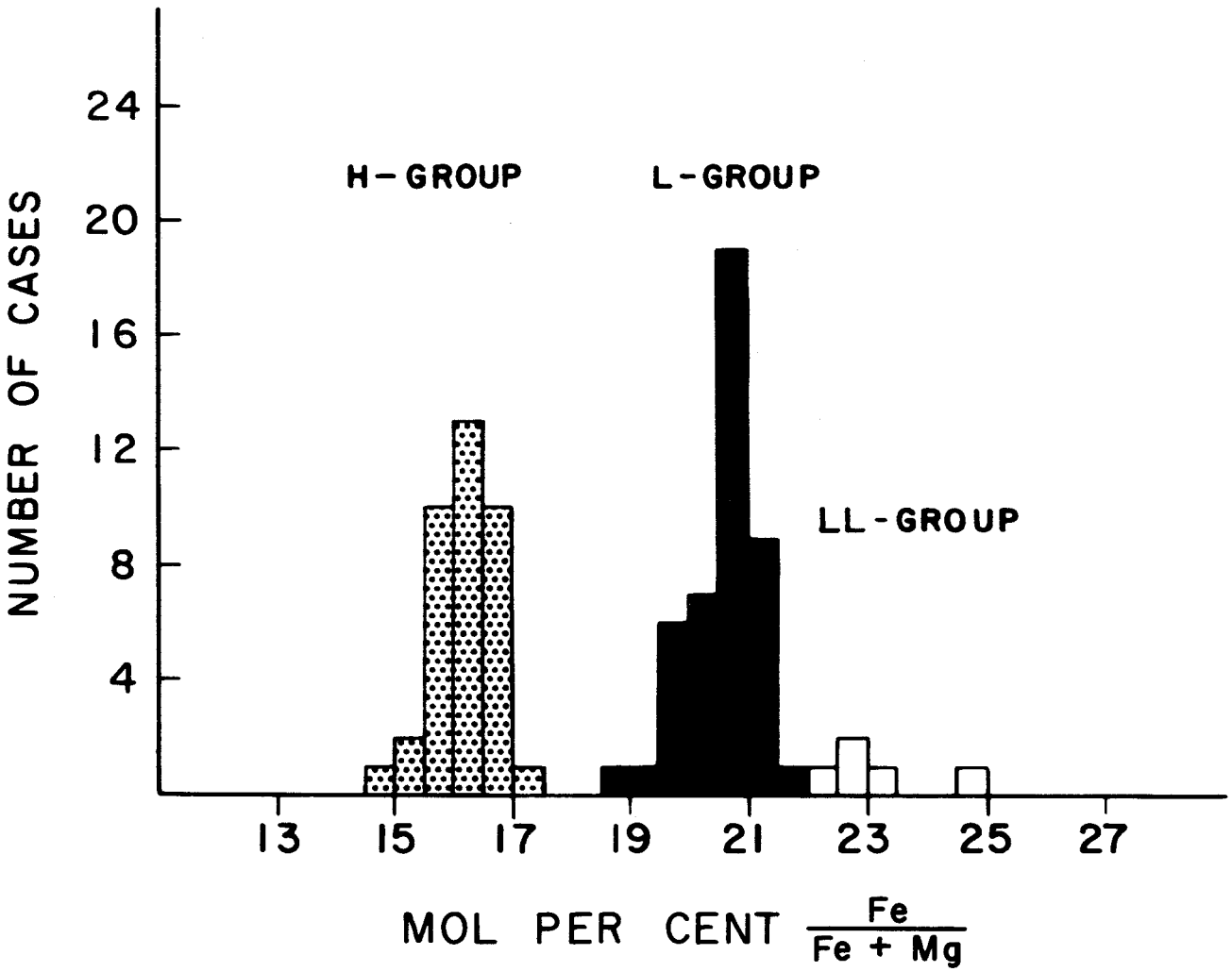


Figure 8.- Frequency distribution of the mol per cent ratios $\frac{Fe}{Fe + Mg}$ in rhombic pyroxene for the chondrites listed in Table 3.

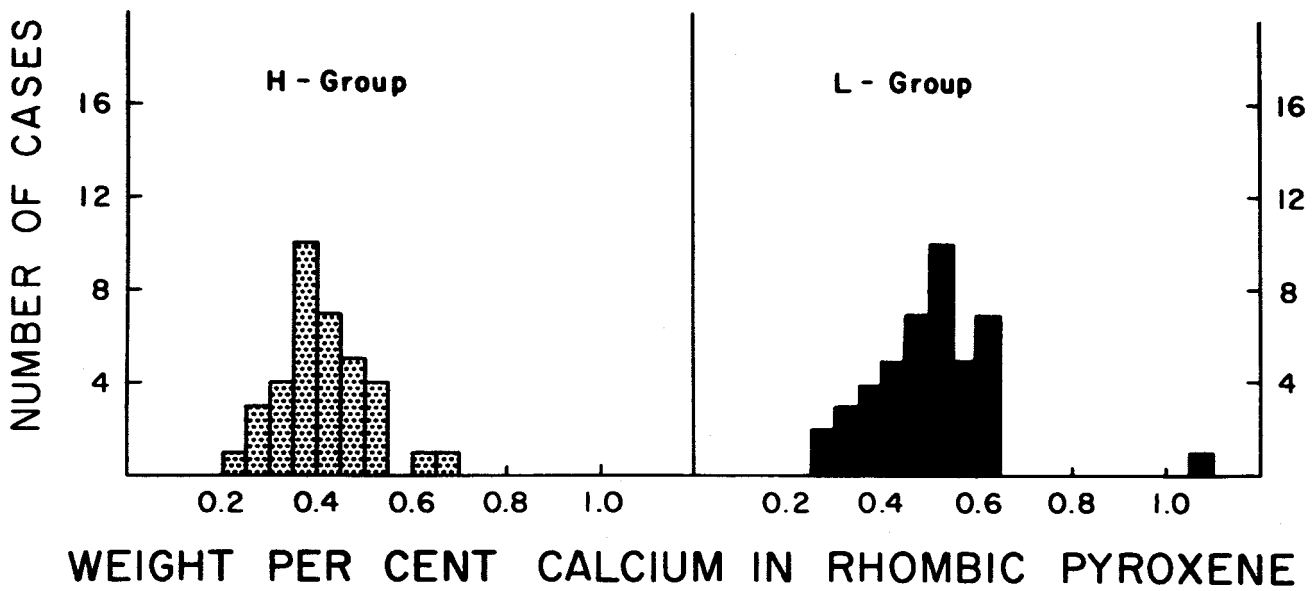


Figure 9.- Frequency distribution of the calcium content of rhombic pyroxenes in the chondrites listed in Table 3.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
AMES RESEARCH CENTER, MOFFETT FIELD, CALIFORNIA

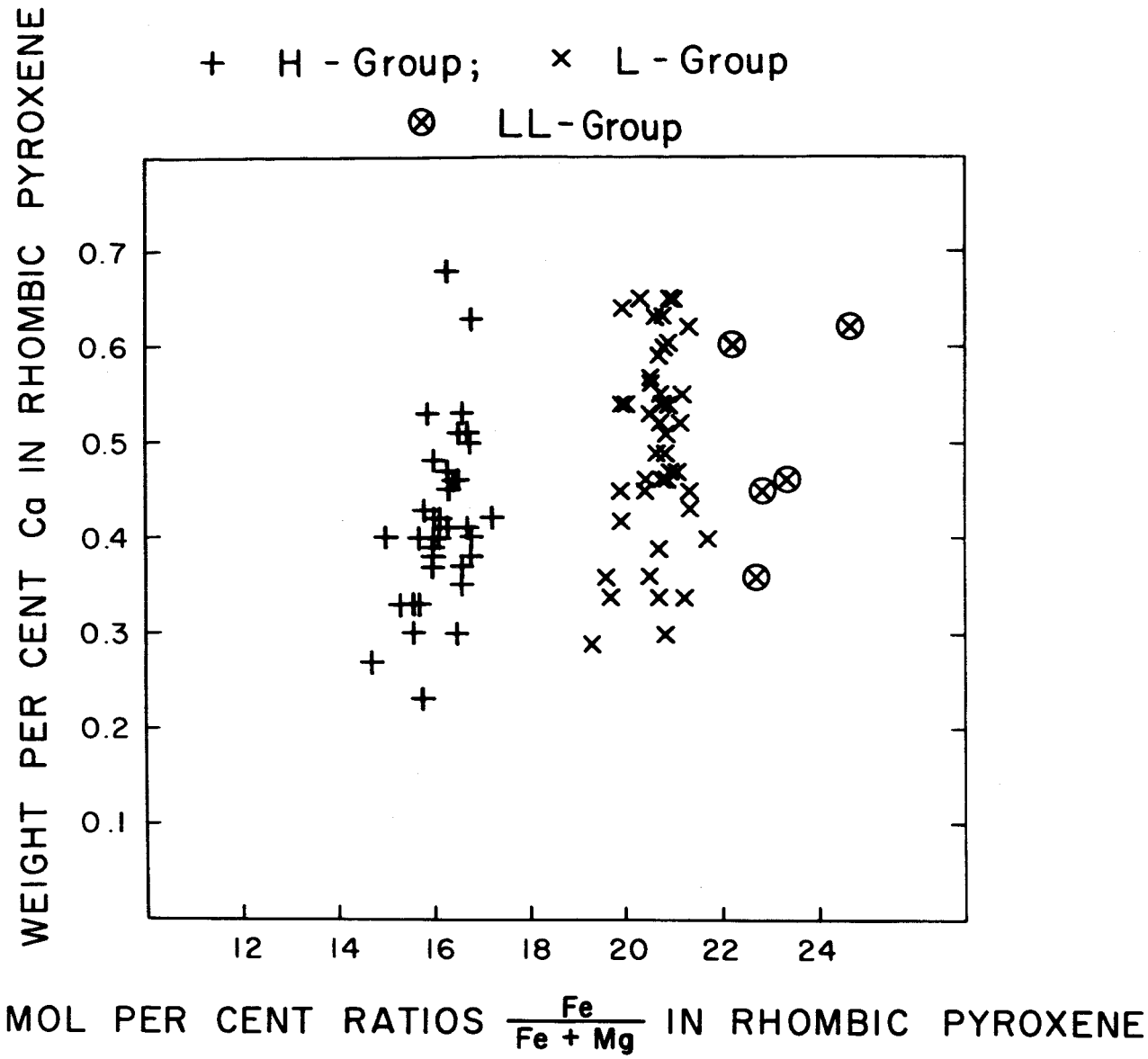


Figure 10.- Calcium content in the rhombic pyroxenes of the chondrites listed in Table 3.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
AMES RESEARCH CENTER, MOFFETT FIELD, CALIFORNIA

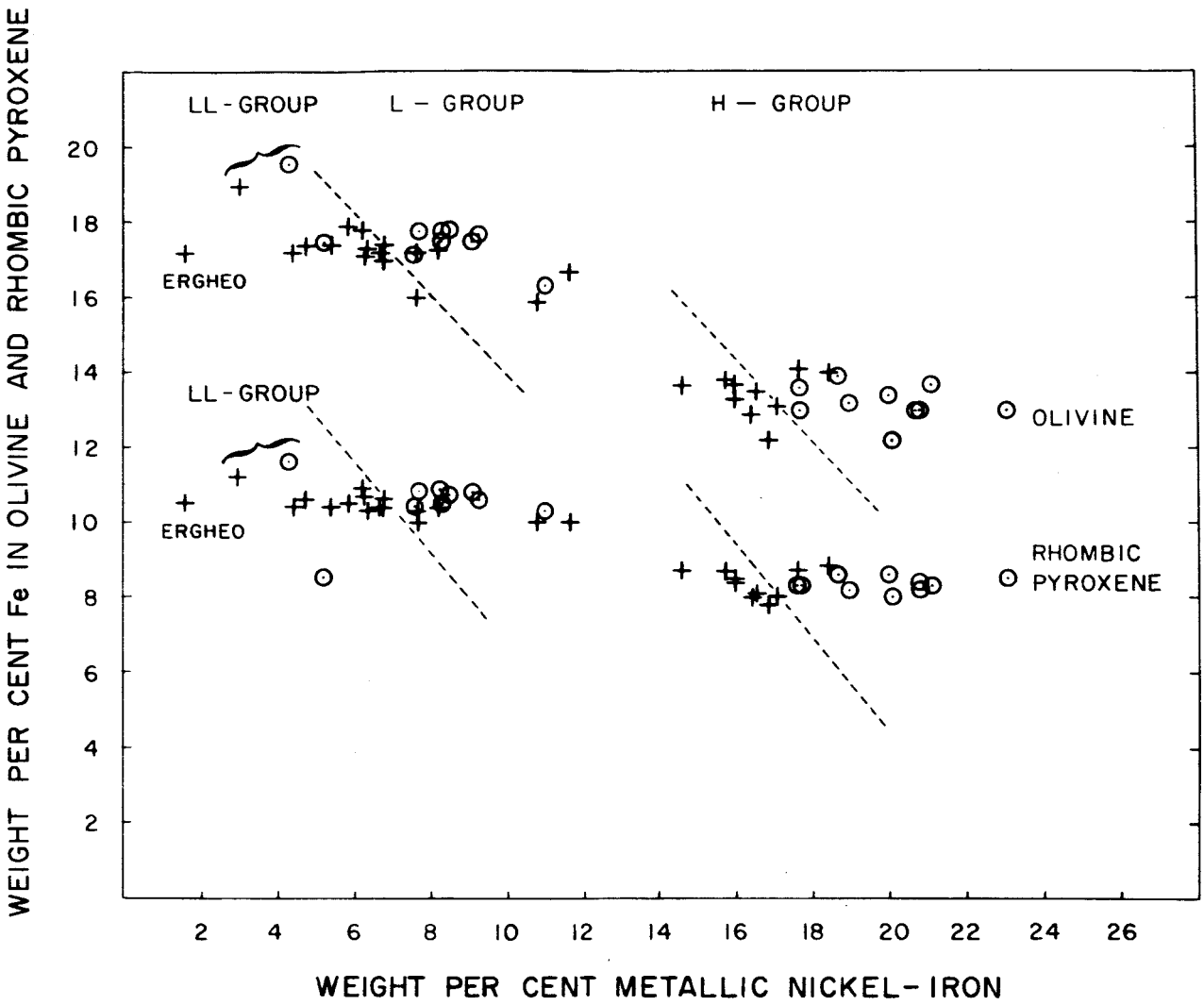


Figure 11.- Relation between the amount of metallic nickel-iron and oxidized iron in olivine and rhombic pyroxene. The metallic nickel-iron values of chondrites, symbolized by crosses, were obtained from papers by Keil [1962a,b]; the values symbolized by circles were obtained from 'superior' chemical analyses of several sources (cf. Table 2).

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
AMES RESEARCH CENTER, MOFFETT FIELD, CALIFORNIA

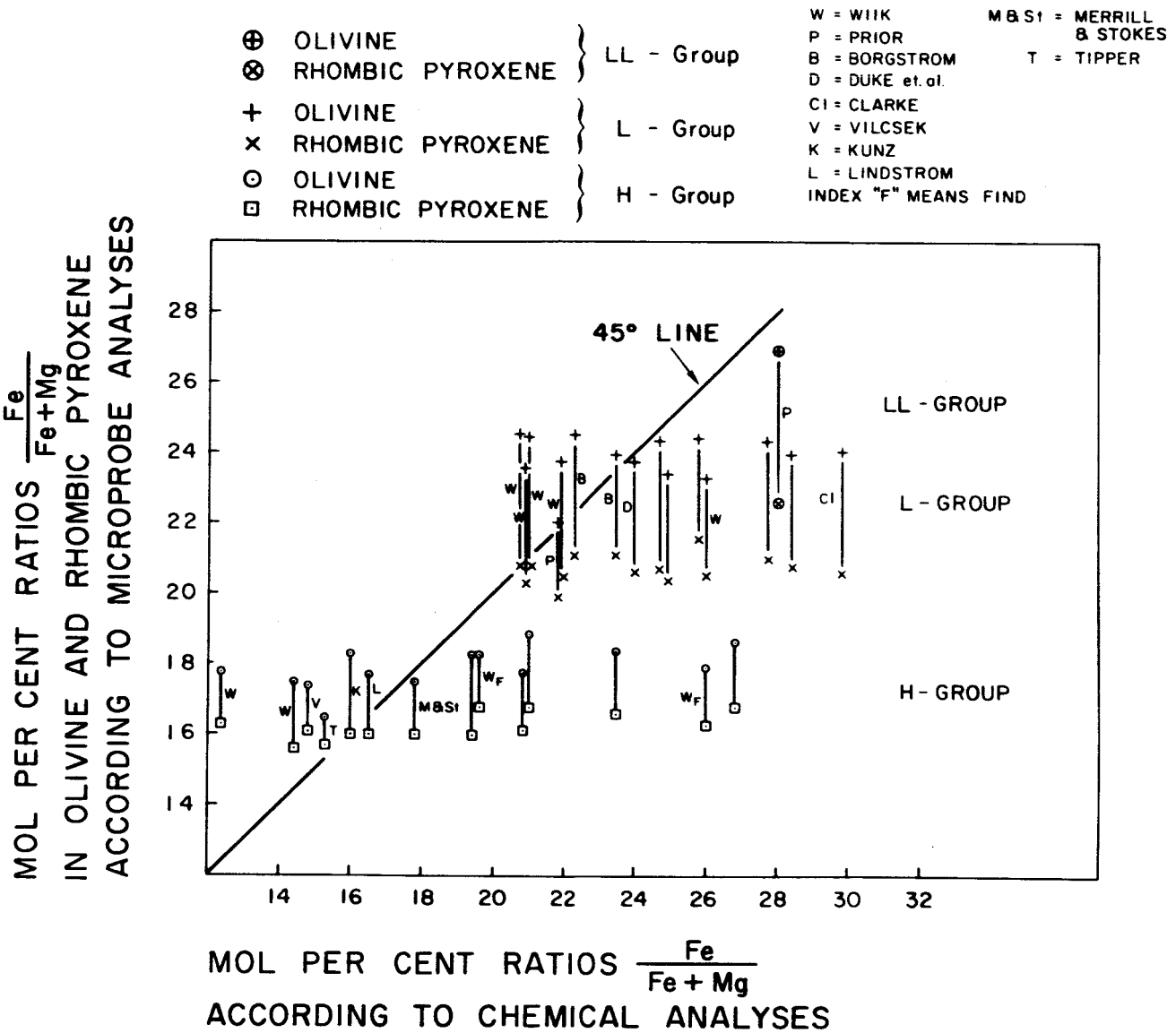
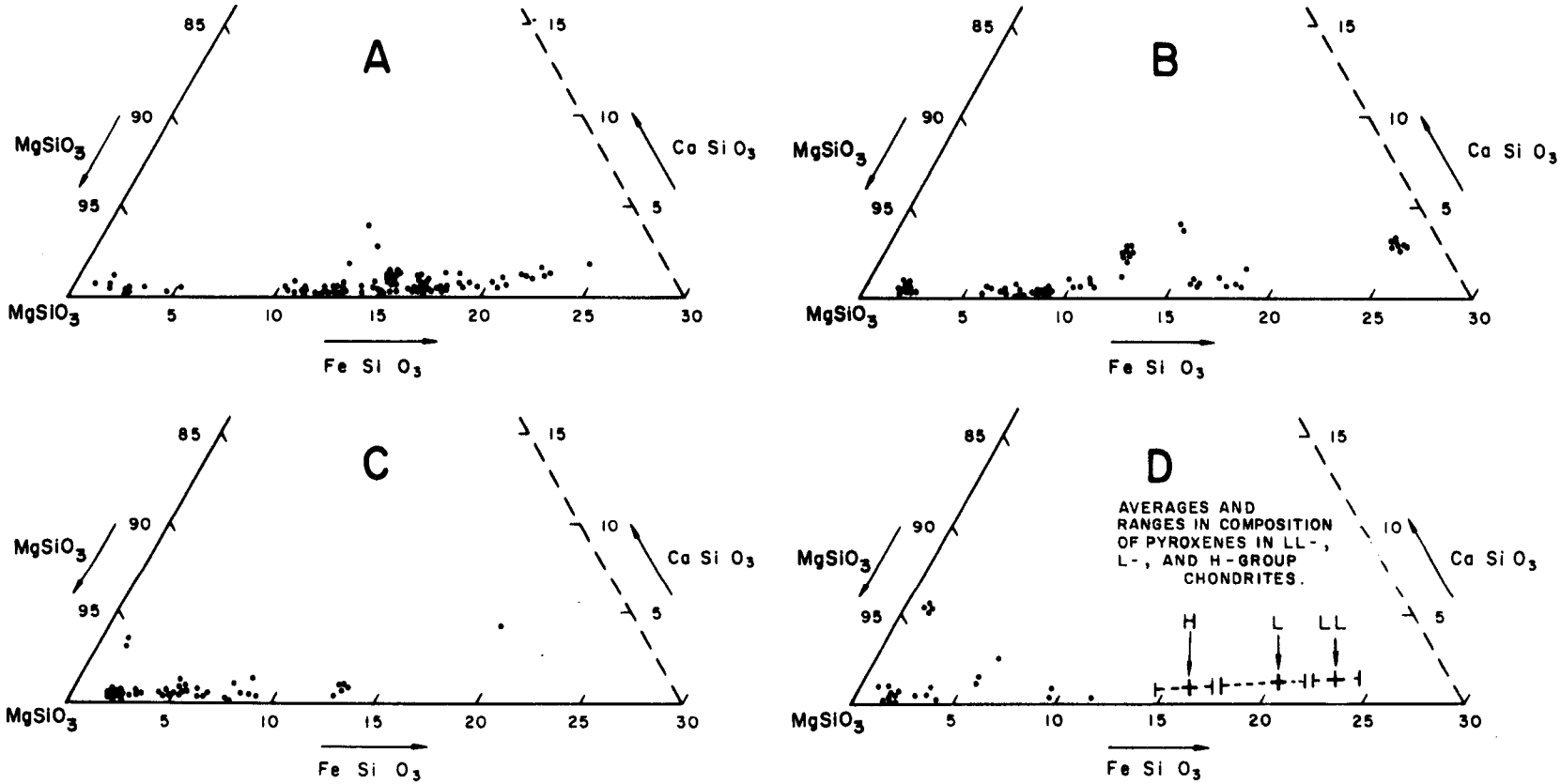


Figure 12.- Mol per cent ratios $\frac{Fe}{Fe + Mg}$ as calculated from FeO and MgO of 'superior' bulk chemical analyses versus ratios $\frac{Fe}{Fe + Mg}$ in olivine and rhombic pyroxene of chondrites obtained by microprobe analyses.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
AMES RESEARCH CENTER, MOFFETT FIELD, CALIFORNIA



(a) 93 pyroxenes from 10 chondrules of a size of 2.0 to 2.5 mm.

(b) 64 pyroxenes from 12 chondrules of a size of 1.0 to 1.4 mm.

(c) 44 pyroxenes from 14 chondrules of a size of 0.4 to 0.6 mm.

(d) 23 pyroxenes from 10 chondrules of a size of 0.3 to 0.4 mm.

Figure 13.- Chondrite Chainpur. Composition of individual pyroxene crystals from individual chondrules, plotted in $MgSiO_3$-$FeSiO_3$-$CaSiO_3$ concentration triangles.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
AMES RESEARCH CENTER MOFFETT FIELD, CALIFORNIA

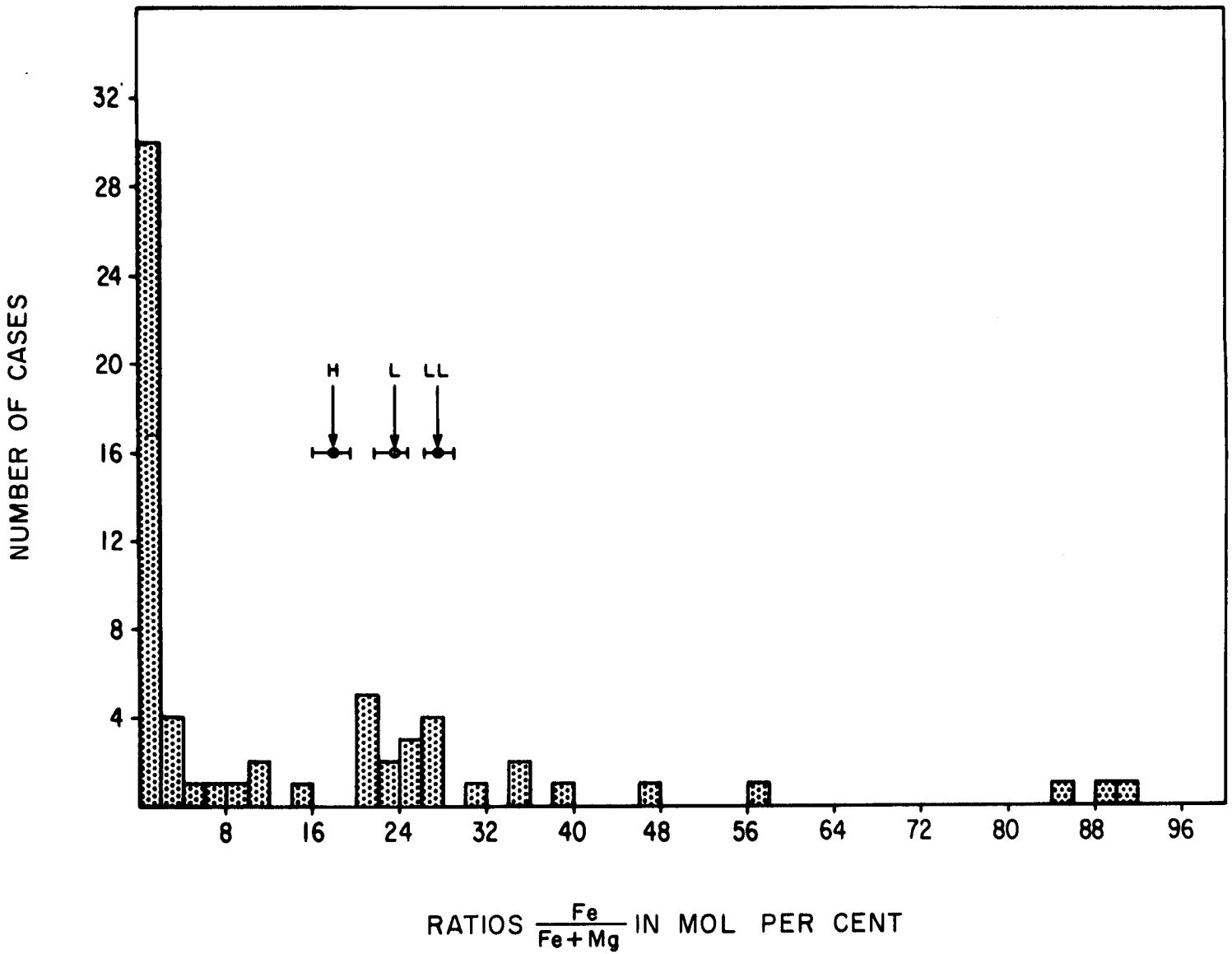


Figure 14.- Carbonaceous chondrite Murray. Frequency distribution of the mol per cent ratios $\frac{Fe}{Fe + Mg}$ in 63 individual olivine crystals.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
AMES RESEARCH CENTER, MOFFETT FIELD, CALIFORNIA

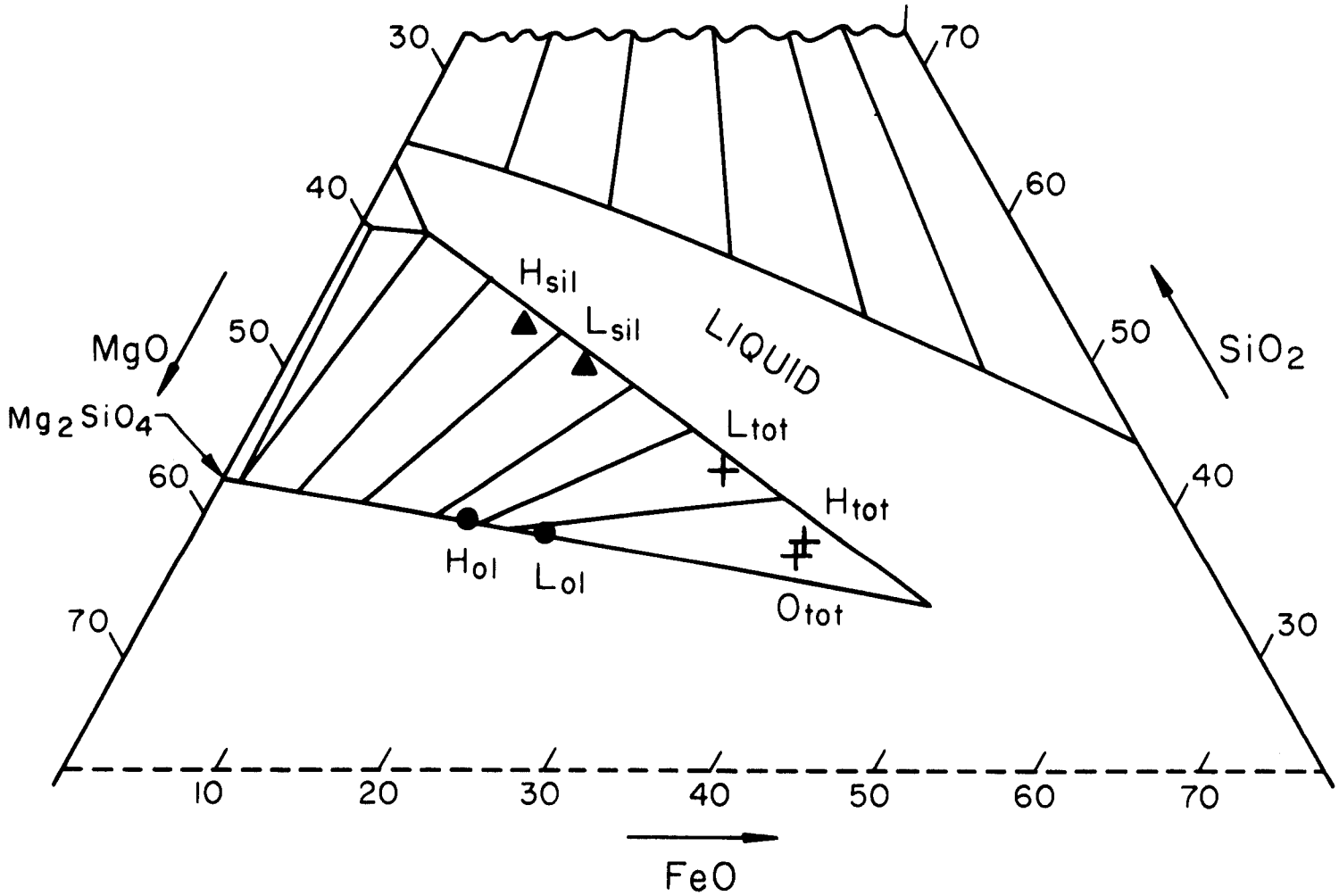


Figure 15.- Phase relations of 1550°C in the MgO-FeO-SiO_2 system after Bowen and Schairer [1935]. L_{sil} and H_{sil} show average MgO, FeO, and SiO_2 for L- and H-group chondrites; H_{tot} and L_{tot} were calculated from these values by adding FeO corresponding to average metallic Fe contents; O_{tot} represents the carbonaceous chondrite Orgueil. H_{ol} and L_{ol} indicate average olivine compositions. The figure illustrates that more ferrous iron than now in the silicates was present during olivine crystallization. Note also that from H_{tot} to H_{sil} the melting point remains practically constant $\gtrsim$ 1550°C, i.e., above the melting point of nickel-iron.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
AMES RESEARCH CENTER, MOFFETT FIELD, CALIFORNIA